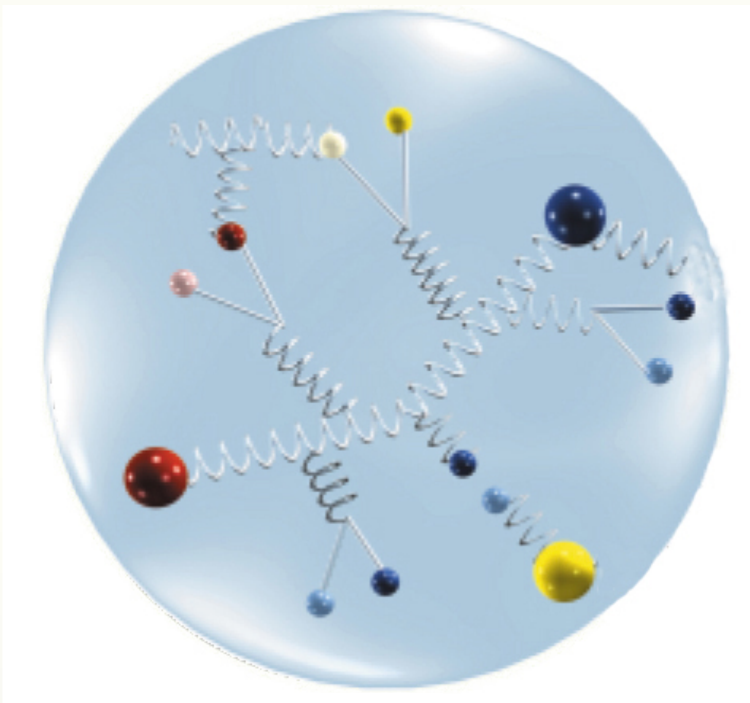
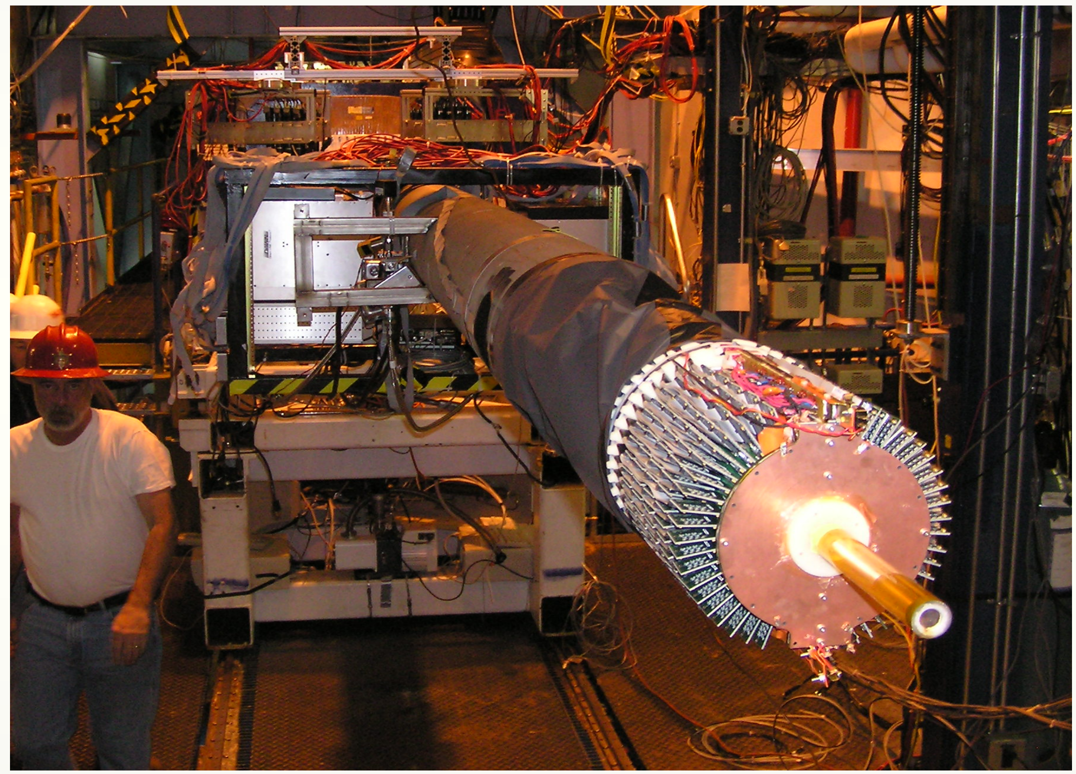
The Structure of (Free) Neutrons at Large $x_{Bjorken}$



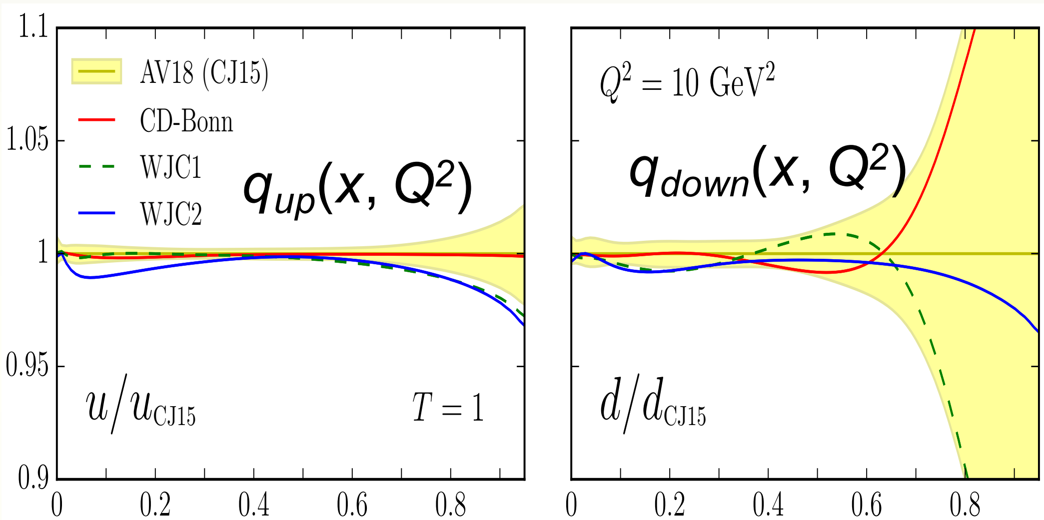


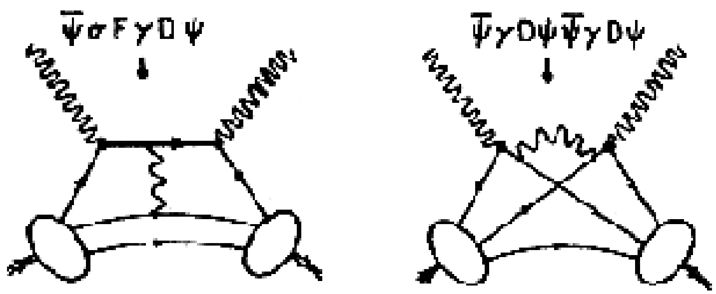
Narbe Kalantarians
Hampton University

2016 Users' Meeting

Structure Functions and Moments: Why large x? Why neutron?

$$\frac{d\sigma}{d\Omega dE'} = \sigma_{Mott}\left(\frac{F_2(x)}{\nu} + 2\tan^2\frac{\theta_e}{2}\frac{F_1(x)}{M}\right); \quad F_2(x,Q^2) = x \sum_{f=up,down,\ldots} z_f^2\left(q_f(x,Q^2) + \bar{q}_f(x,Q^2)\right)$$



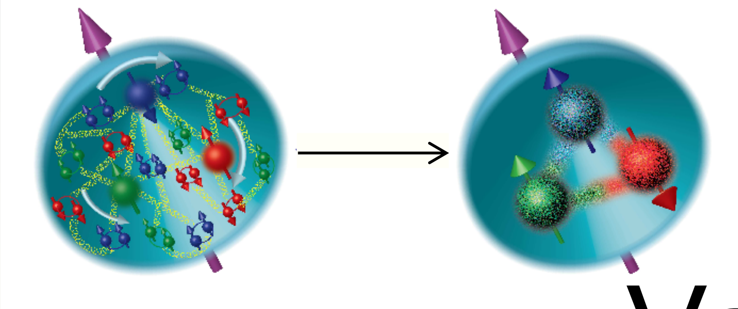


$\tau = 4$

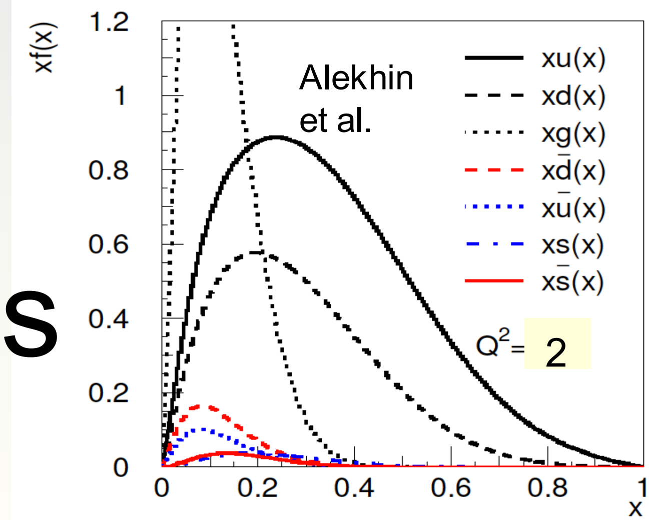
- $q_f(x\text{->}1)$ for both nucleons is a crucial test of valence quark models
  - Isospin, SU(6) breaking, pQCD,…
- Precise PDFs at large *x* needed as input for LHC, ν experiments etc.
  - Large *x*, medium Q^2 evolves to medium *x*, large Q^2
  - Also: NUCLEAR structure functions
- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large *x*
- Quark-Hadron Duality

$$M_n^{CN}(Q^2) = \int_0^\infty dx\, \underline{x^{(n-2)}} F_2(x,Q^2) = \sum_{\tau=2k}^{\infty} E_{n\tau}(\mu,Q^2) O_{n\tau}(\mu) \left(\frac{\mu^2}{Q^2}\right)^{\frac{1}{2}(\tau-2)}$$

+ TM corr.



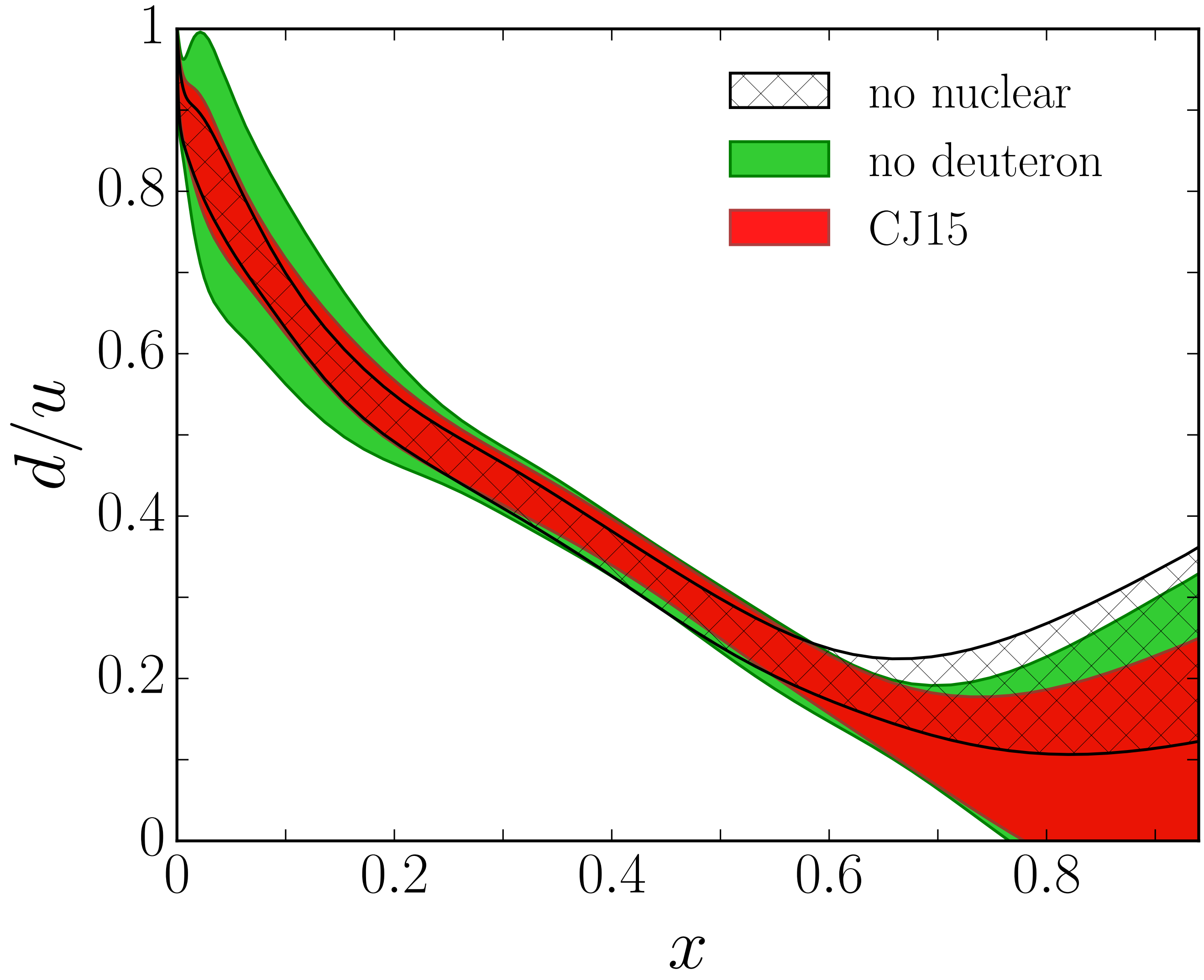
Valence PDFs



CJ15

- Behavior of PDFs still unknown for x -> 1
  - SU(6): d/u = 1/2, $\Delta u/u$ = 2/3, $\Delta d/d$ = -1/3 for all x
  - Relativistic Quark model: Δu, Δd reduced
  - Hyperfine effect (1-gluon-exchange): Spectator spin 1 suppressed, d/u -> 0, $\Delta u/u$ -> 1, $\Delta d/d$ -> -1/3
  - Helicity conservation (pQCD): Spectator spin $S_z \neq 0$ suppressed, d/u -> 1/5, $\Delta u/u$ -> 1, $\Delta d/d$ -> 1
  - Orbital angular momentum: can explain slower convergence to $\Delta d/d = 1$
- Plenty of data on proton; mostly constraints on u and Δu
- Knowledge on d limited by lack of free neutron target (nuclear binding effects in D, ^{3}He)
- Large x requires very high luminosity and resolution; binding effects become dominant uncertainty for the neutron

Large *x* - Large Nuclear Effects



- Even simple "Fermi Smearing" leads to significant dependence on D wave function
- Different models for off-shell and "EMC" effects lead to large additional variations
- Contributions from MEC, Δ1232) and "exotic" degrees of freedom unknown
- FSI?

Present Knowledge of *d*/*u* (*x* -> 1)

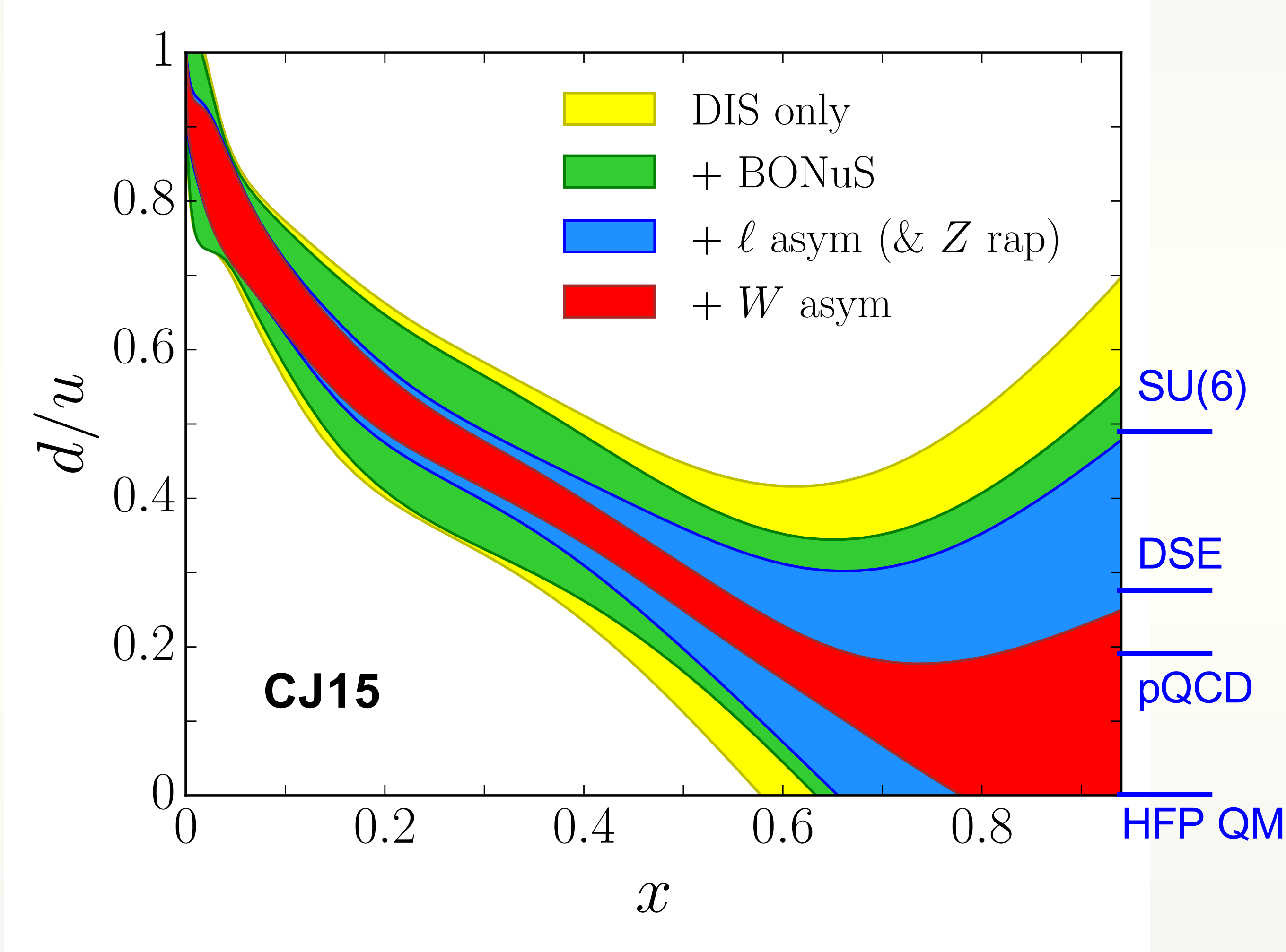
Assuming charge independence (= invariance under 180° rotations in isospin space):

$$\frac{F_{2n}}{F_{2p}} \approx \frac{1+4\,d/u}{4+d/u} \Rightarrow$$

$$\frac{d}{u} \approx \frac{4\,F_{2n}/F_{2p}-1}{4-F_{2n}/F_{2p}}$$

$F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1$

???

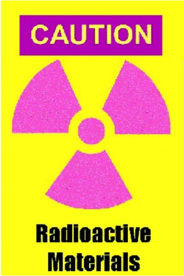


- Neutron data limited by "Nuclear Binding Uncertainties"

Neutron Data Are Important…
…but hard to get

• Free neutrons decay in 15 minutes.

• Radioactivity!



• Zero charge makes it difficult to create a dense target

Magnetic bottle: 10^3 - 10^4 n/cm^2 [TU München]

Typical proton target: $4 \cdot 10^{23}$ p/cm^2 [10 cm LH] – 10^{14} p/cm^2 [HERMES]

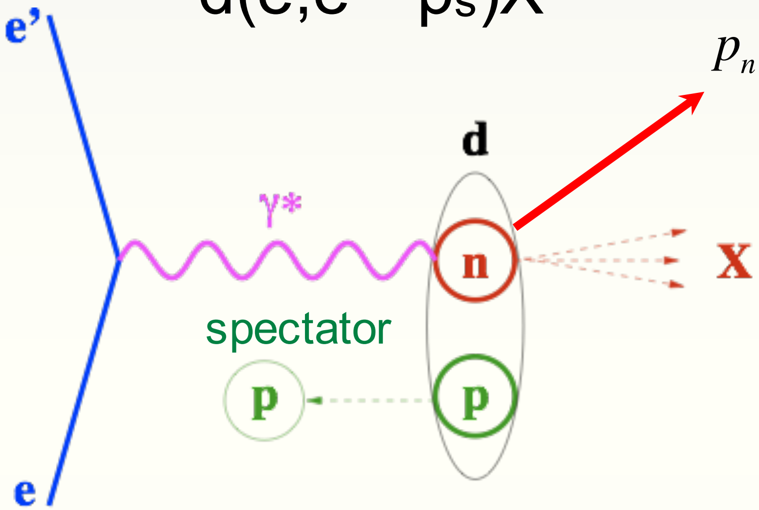
=> Alternative Solution: Deuterons, Tritons and Helium-3…

BUT: Nuclear Model Uncertainties:

Fermi motion, off-shell effects (binding), structure modifications (EMC effect), extra pions/Deltas, coherent effects, 6-quark bags…

Spectator Tagging

d(e,e' p_s)X

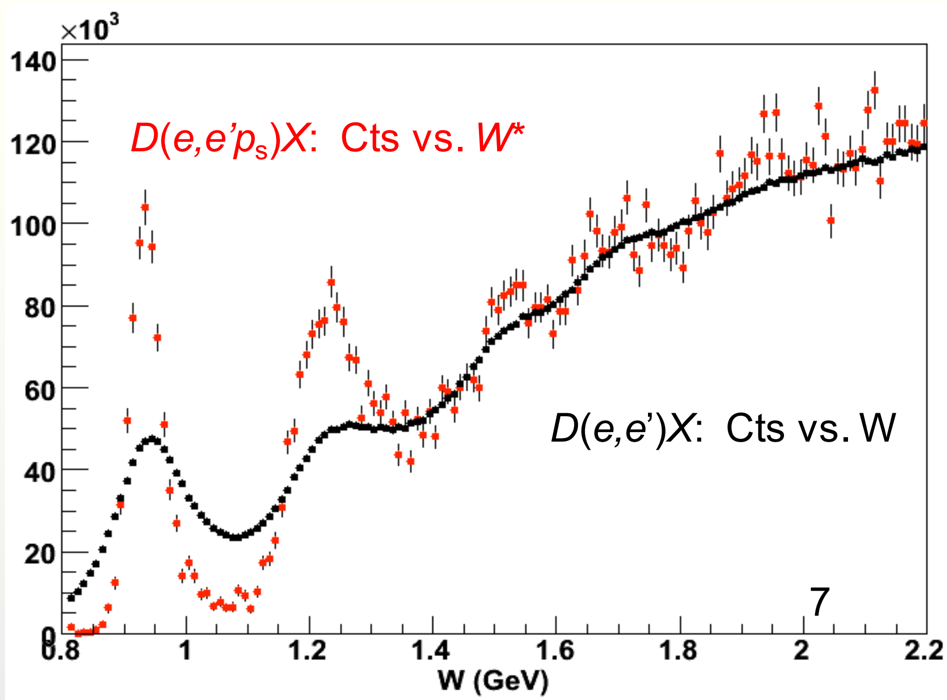


$$p_n = \left(M_D - E_S, -\vec{p}_S\right); \alpha_n = 2 - \alpha_S \qquad M^{*2} = p_n^{\mu} p_{n\mu}$$

$$p_S = \left(E_S, \vec{p}_S\right); \qquad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D / 2}$$

$$\boxed{x = \frac{Q^2}{2 p_n{}^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2-\alpha_S)}}$$

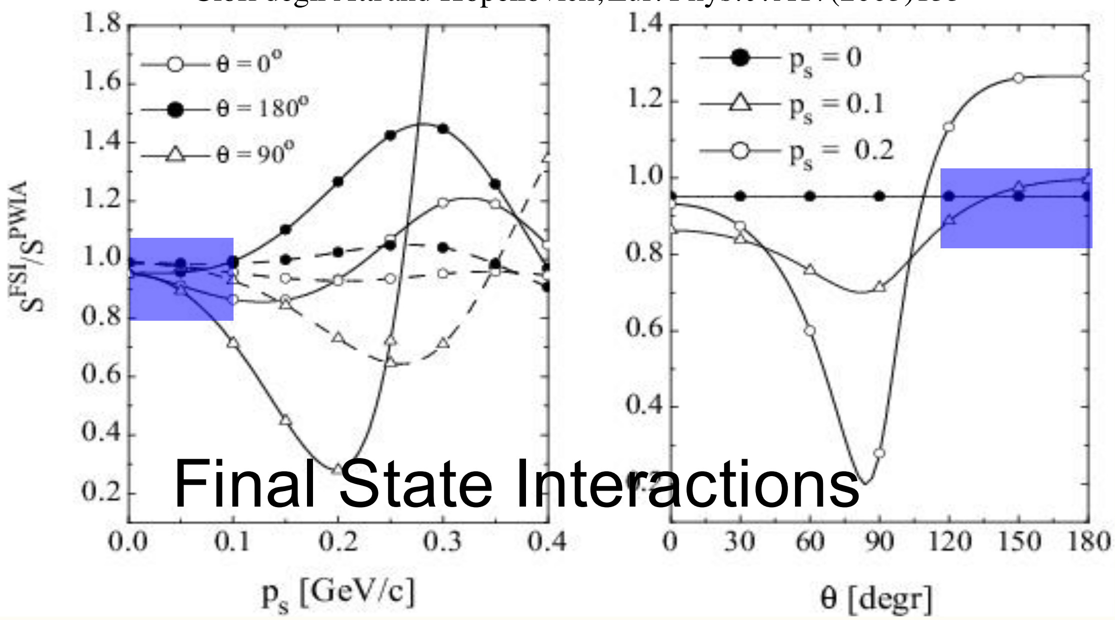
$$\boxed{\begin{aligned} W^{*2} &= \left(p_n + q\right)^2 = M^{*2} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2 \\ &\approx M^{*2} + 2M\nu(2-\alpha_S) - Q^2 \end{aligned}}$$

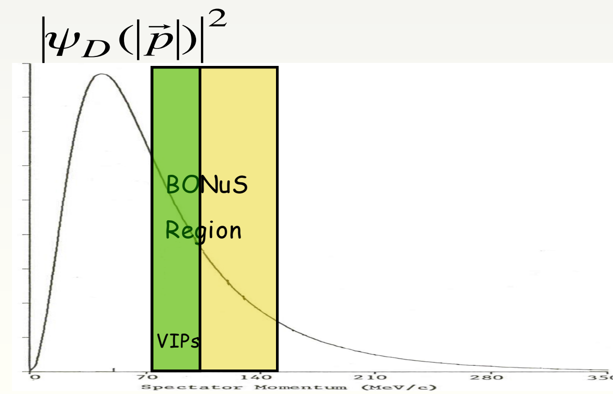


Spectator Tagging

Limitations

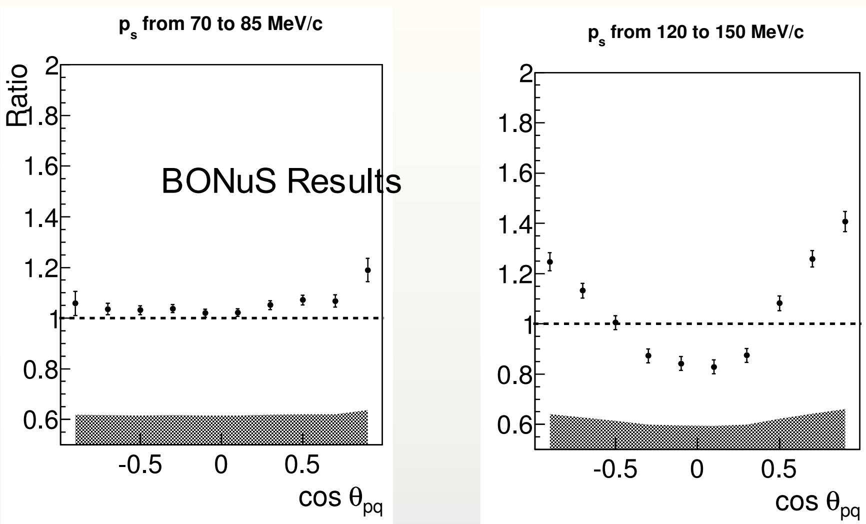
Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133



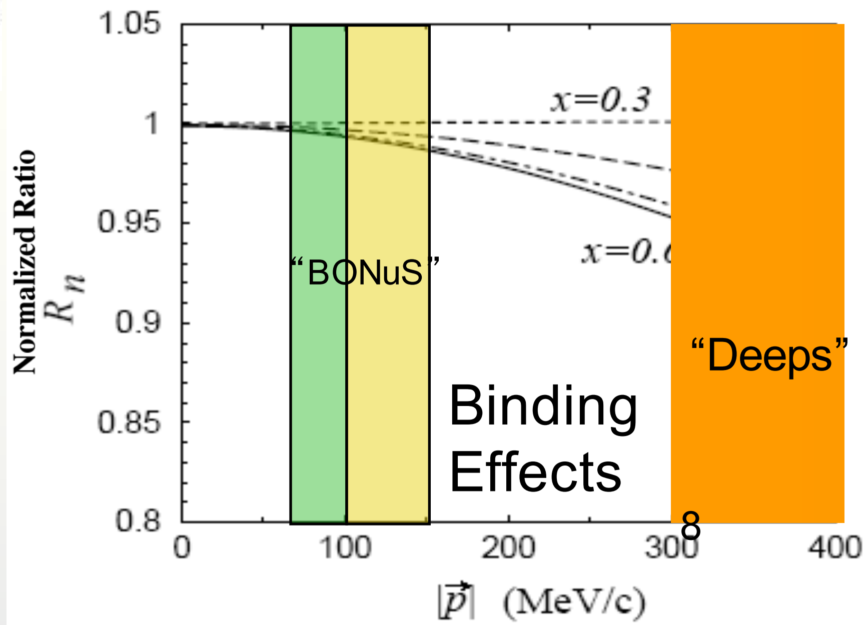


0.07 0.2 GeV/c

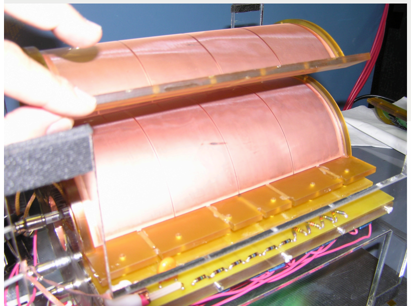
Finite coverage of WF



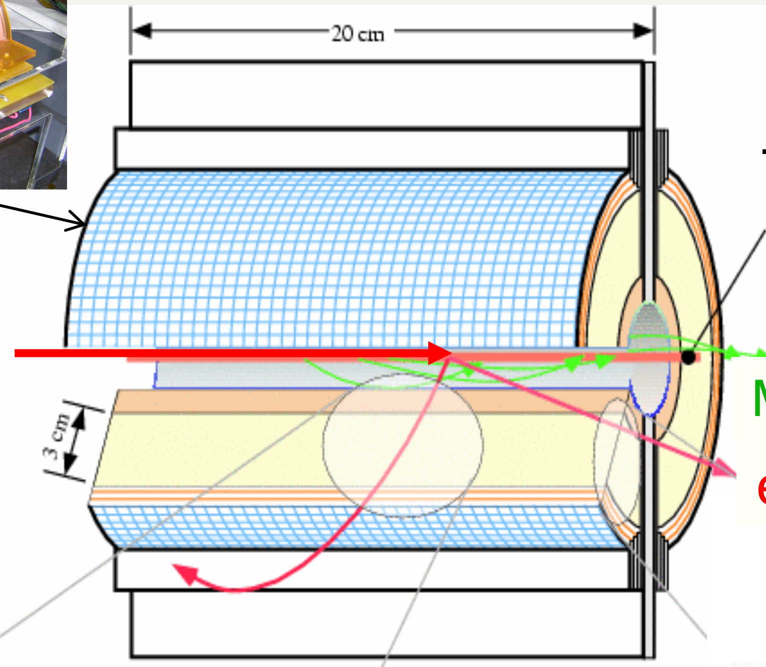
$$R_n \equiv F_2^{n(eff)}(W^2, Q^2, p^2)/F_2^n(W^2, Q^2)$$



BoNuS RTPC



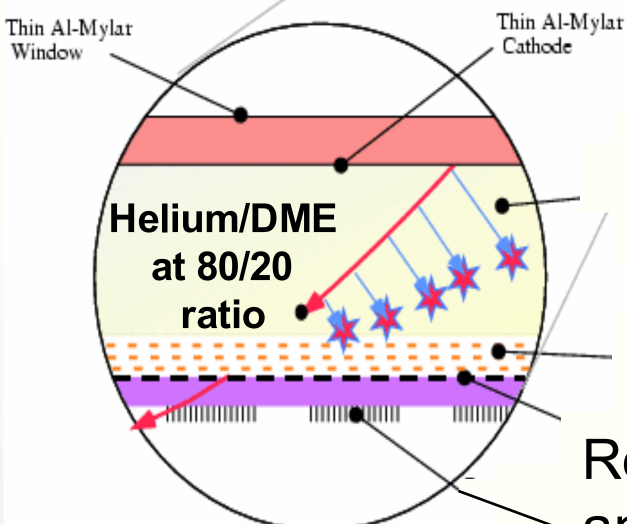
Gas
Electron
Multiplier



7 atm D_2 gas

Møller el.

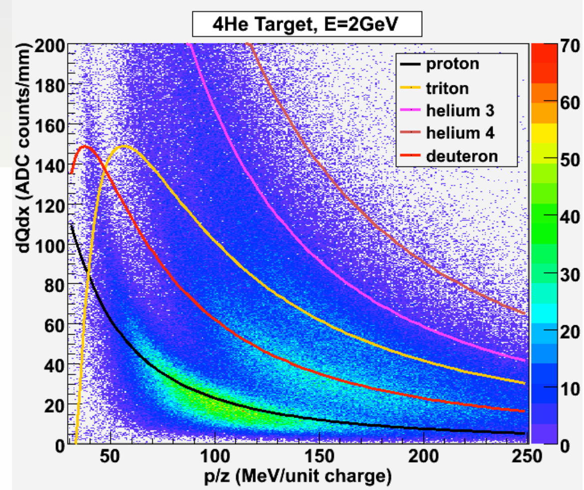
e^- (to CLAS)



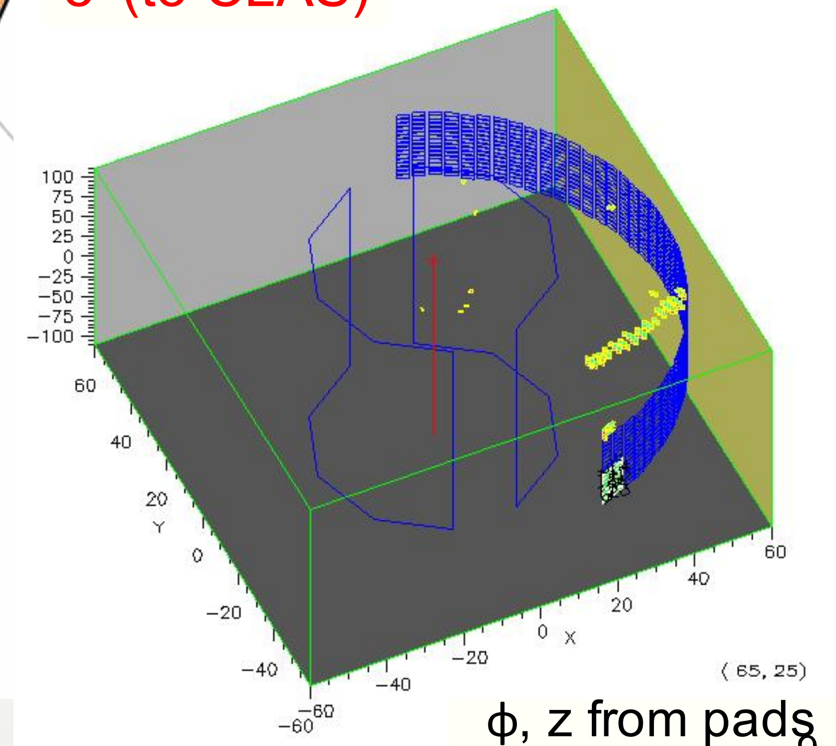
Drift Region

3 GEMs

Readout pads and electronics

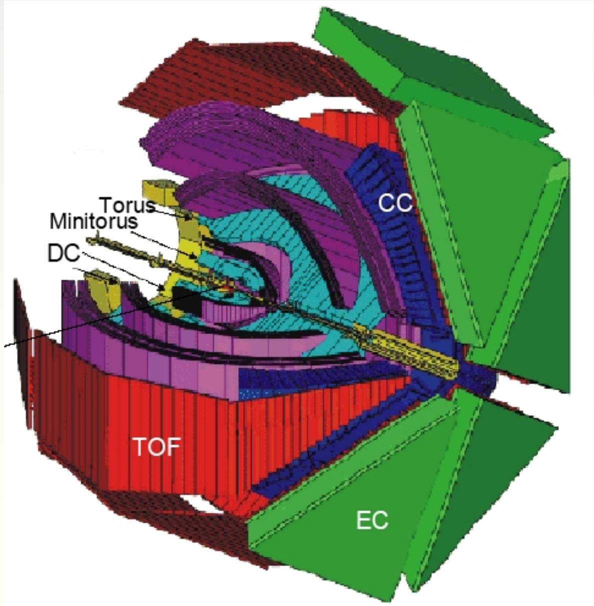


dE/dx from charge along track (particle ID)

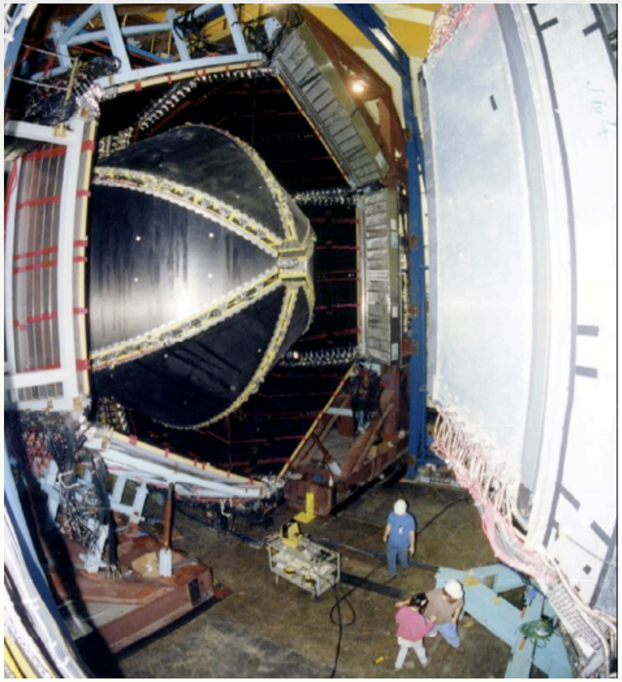


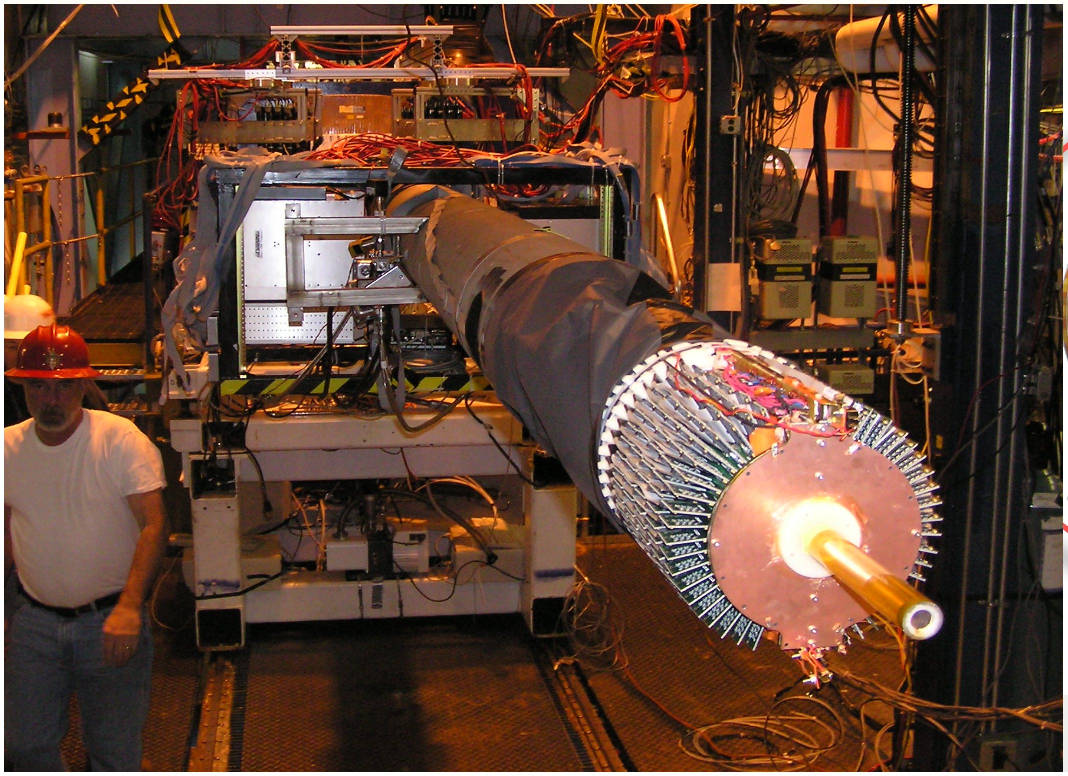
ϕ, z from pads
r from time

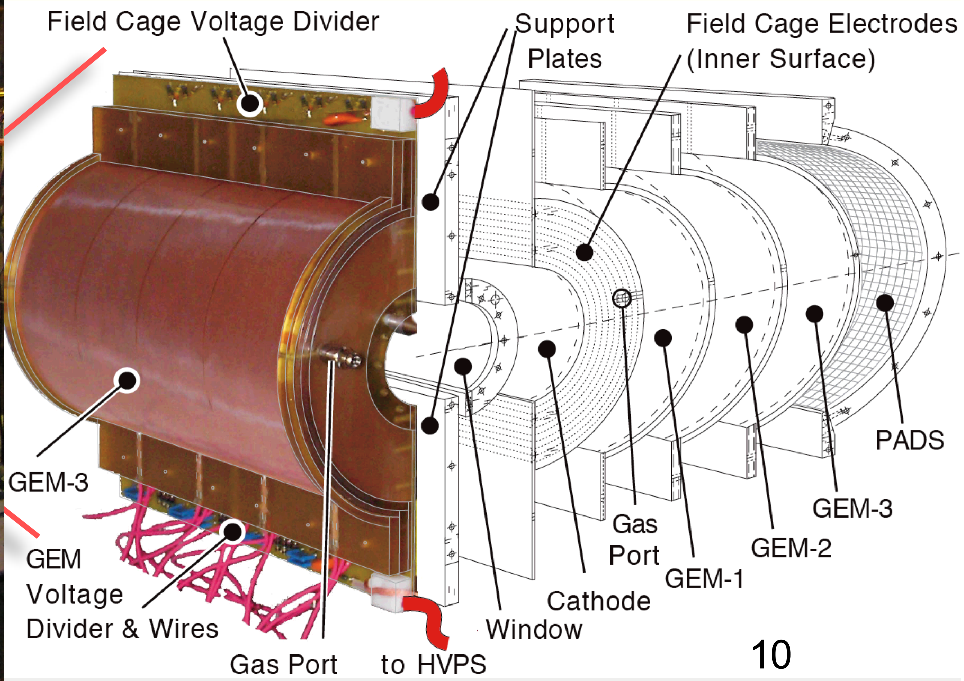
Nucl. Instr. Meth. **A592**, 273 (2008)



BONuS in CLAS



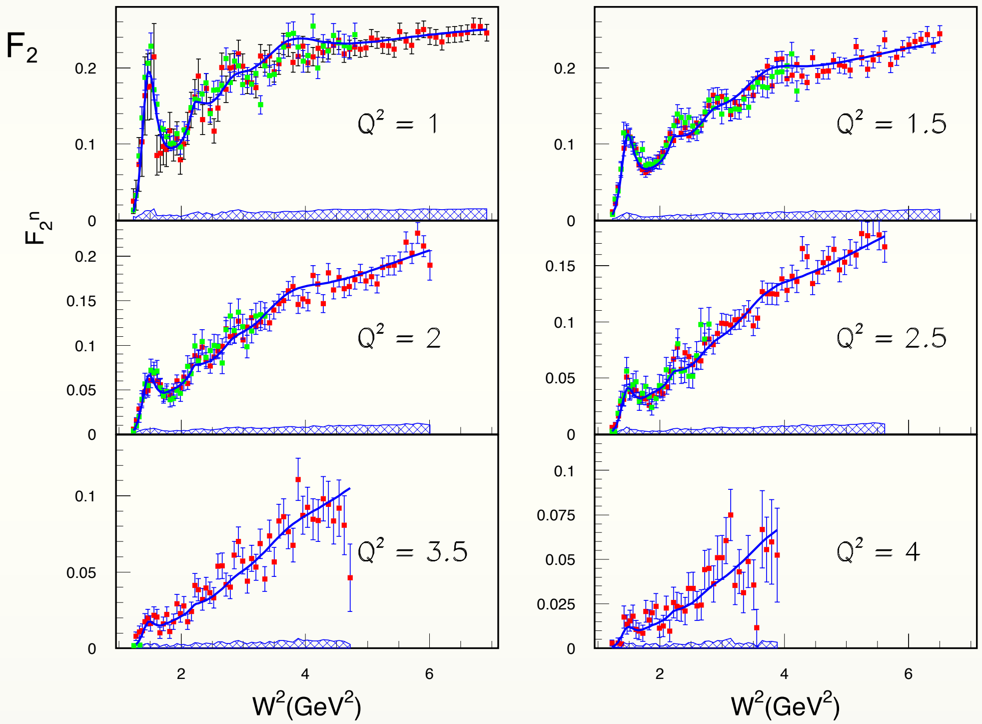


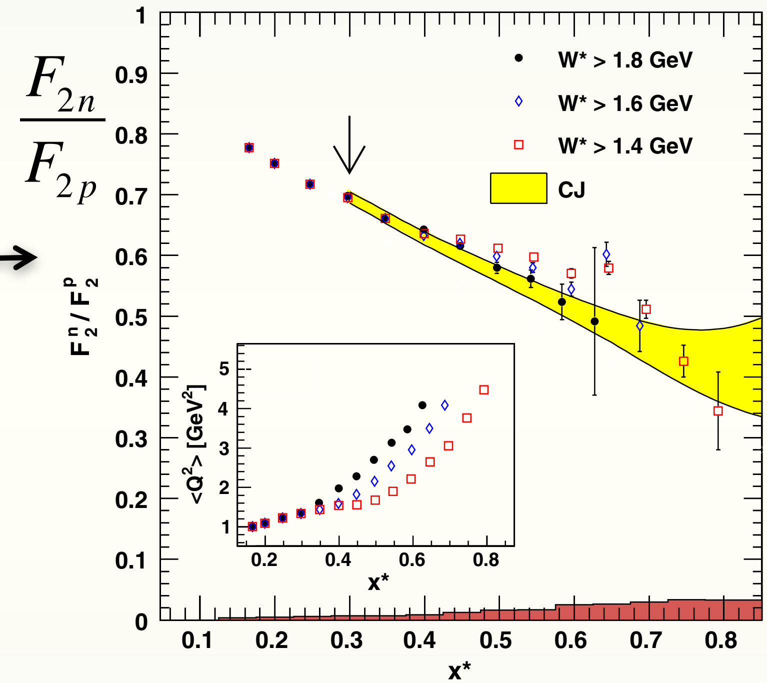


Spectator Tagging

BONuS – Results (1/2)

Phys Rev C **89** 045206 (2014)



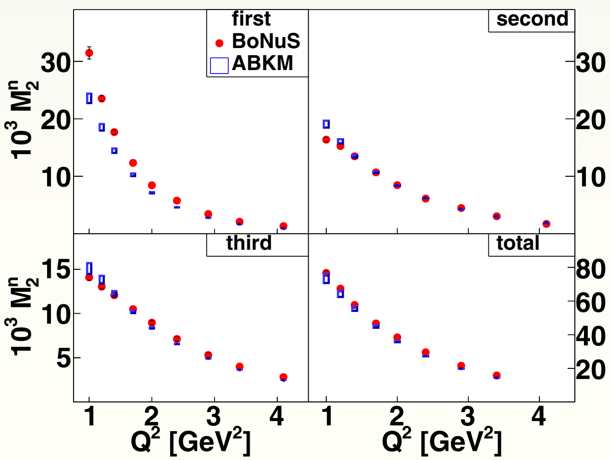


*Textbook Physics (C. Quigg)

Spectator Tagging

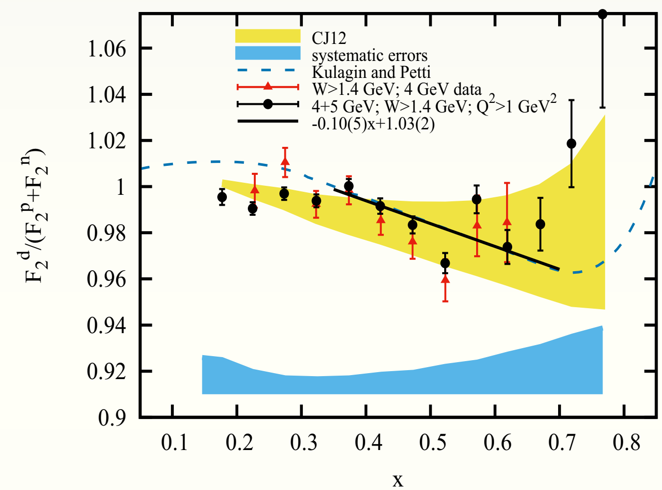
BONuS – Results (2/2)

Duality: Phys Rev C **91** 055206 (2015)

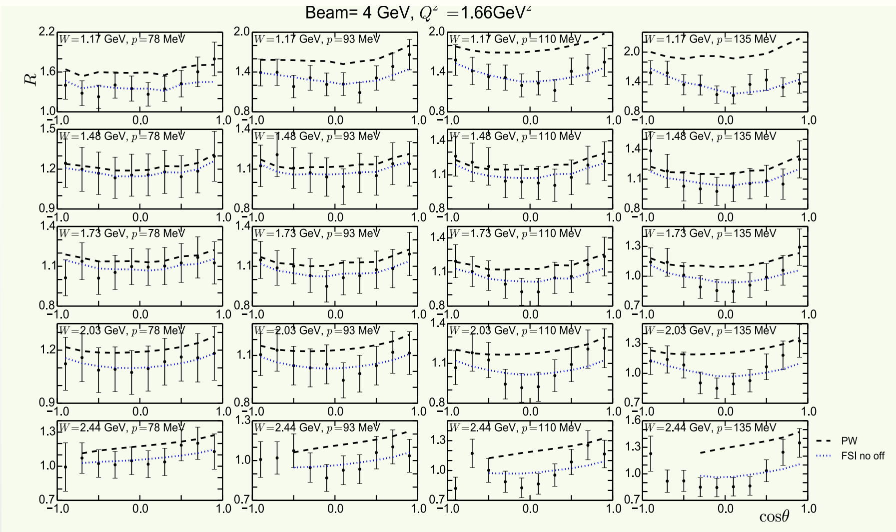


EMC Ratio

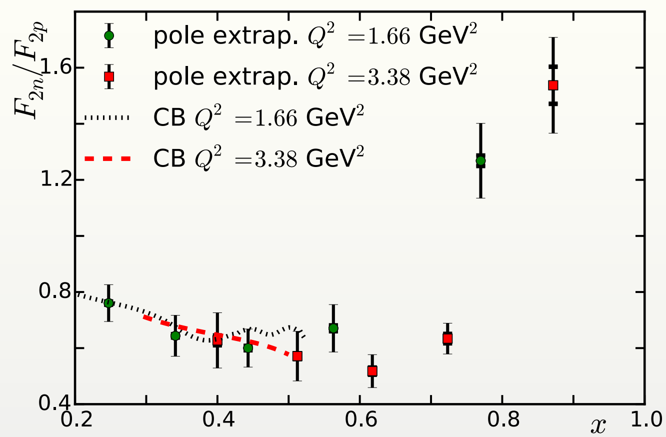
PHYSICAL REVIEW C **92**, 015211 (2015)



FSI: Cosyn, Sargisian *et al.*



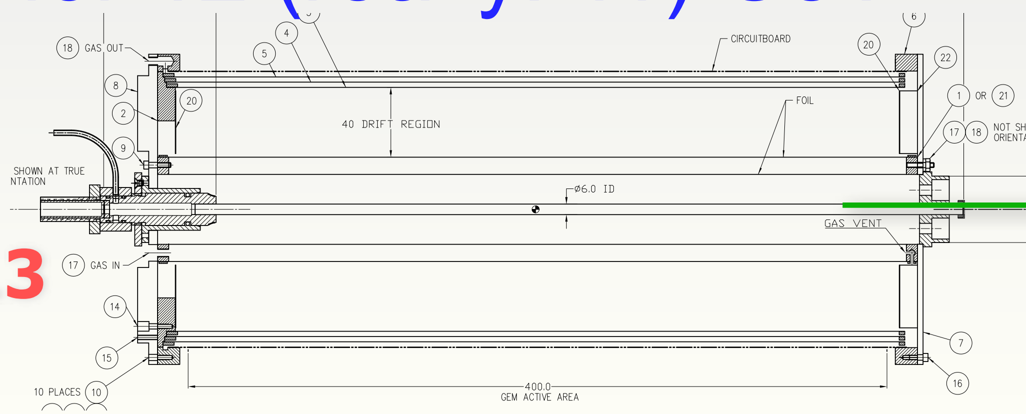
Phys Rev C **93** 055205 (2016)

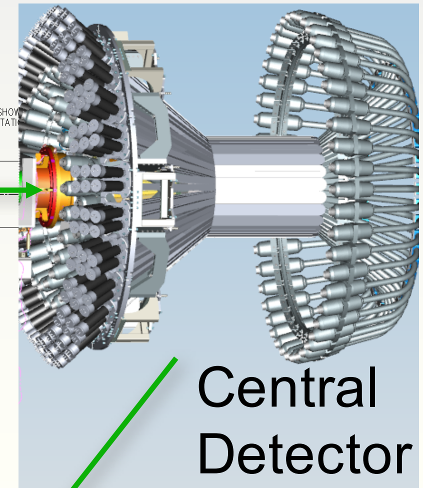


Plans for 12 (really: 11) GeV

BONuS12

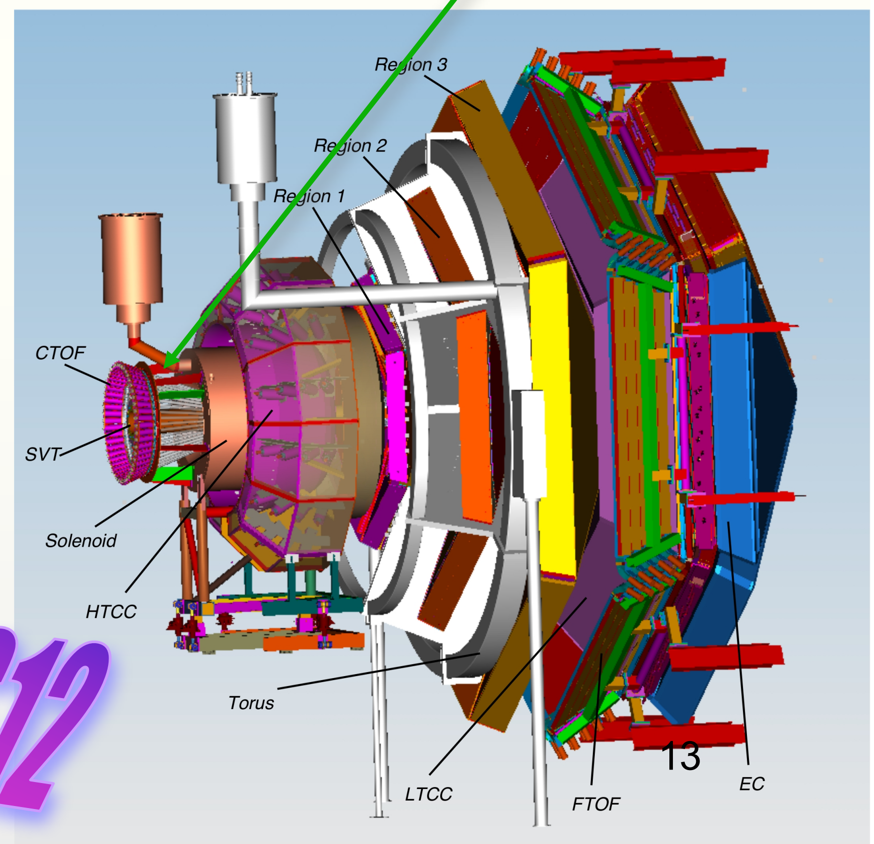
E12-06-113





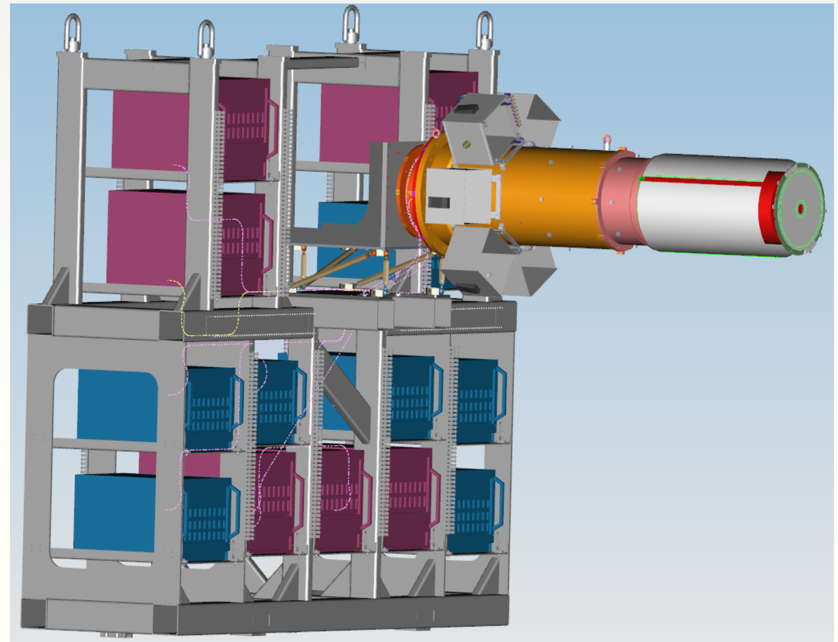
- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$
- **Planned** BONuS detector DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1\ \mathrm{GeV}^2/c^2$
  - $W^* > 2$ GeV
  - $p_s > 70$ MeV/c
  - $10° < \theta_{pq} < 170°$
- Extend to higher momenta using central detector alone

CLAS12

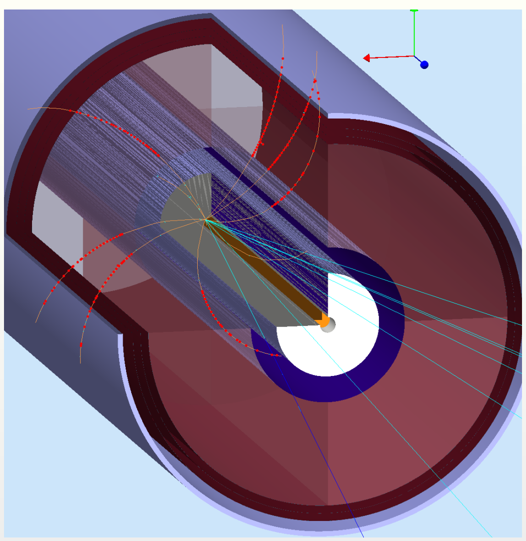


Plans for 12 (really: 11) GeV

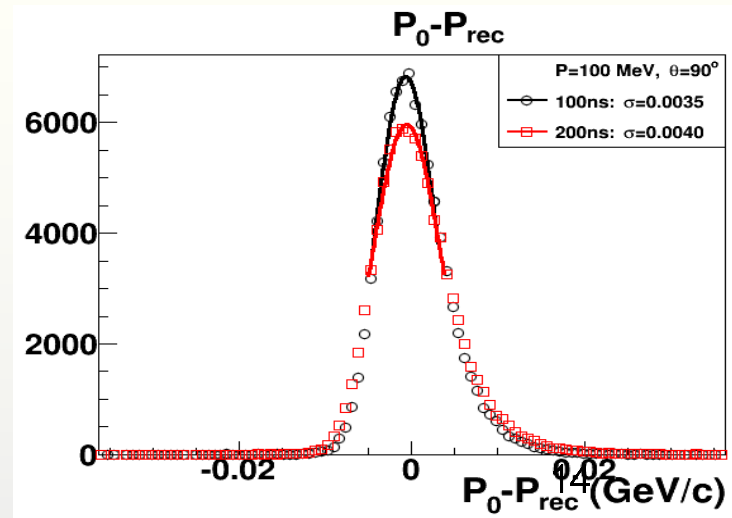
BONuS12 E12-06-113



- Replaces SiVtx and micro-megas barrel trackers
- Trigger rate about 2 KHz
- 18,000 “pads” read out at 5MHz over 10 μs
  1-2 mm radial spacing, 4 cm in z, 2 degrees in phi
  => Fully reconstructed track in 3D, suppression of < 5 MHz background through timing and vertex cuts
- Readout electronics: “DREAM” chip (Saclay)

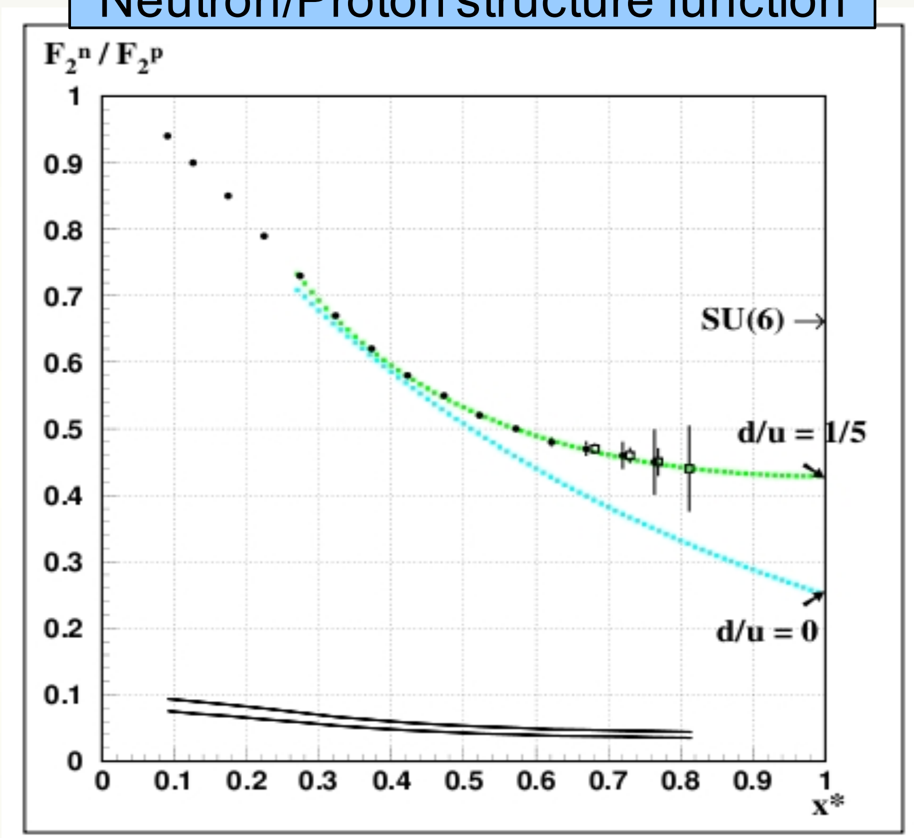


- Full simulation with GEANT-4 based CLAS12 GEMC
- < 4% momentum resolution
- < 2mm vertex resolution

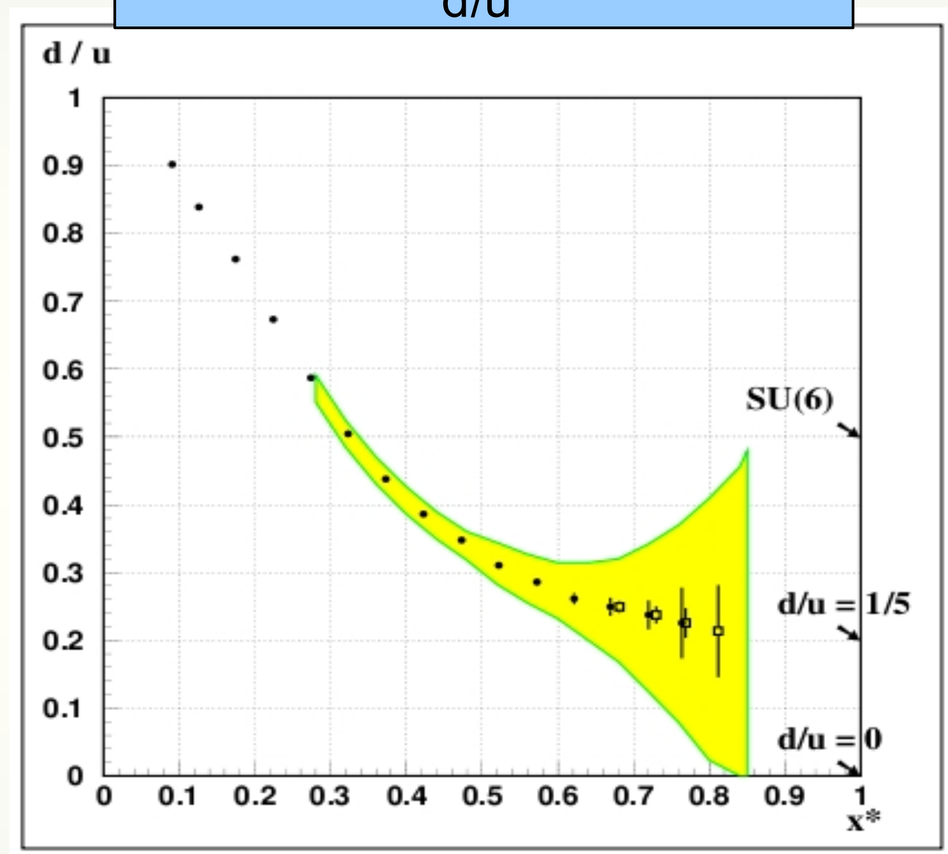


Expected Results

Neutron/Proton structure function



d/u



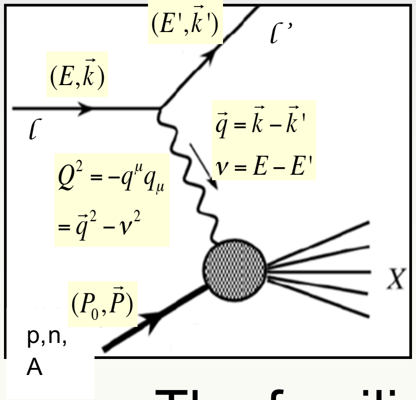
Dark Symbols: W* > 2 GeV (x* up to 0.8, bin centered x* = 0.76)

Open Symbols: "Relaxed cut" W* > 1.8 GeV (x* up to 0.83)

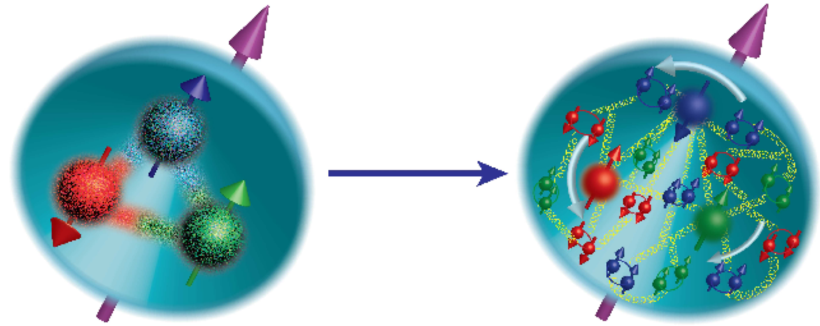
Summary

- F_2^n (for x -> 1) highly crucial for numerous topics in nuclear and particle physics.
- It is not easy to get neutron information. Spectator tagging is one method for this.
- **BONuS** @*6* GeV demonstrated that spectator tagging method works. And produced results!
- **BONuS** @*12* GeV intends to further coverage in *x,* with new (& enhanced) RTPC.
- Design, planning, and simulations are in progress.
- New, interested collaborators are welcome!

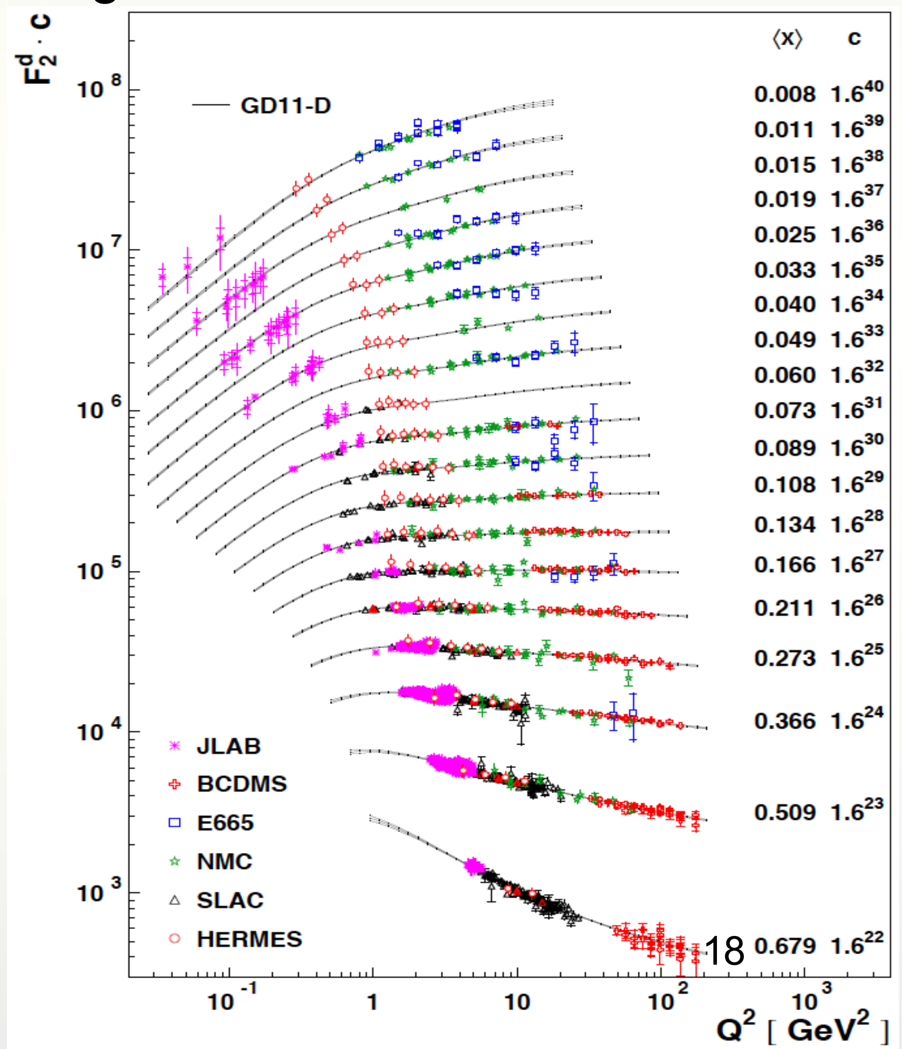
Backup Slides



Motivation



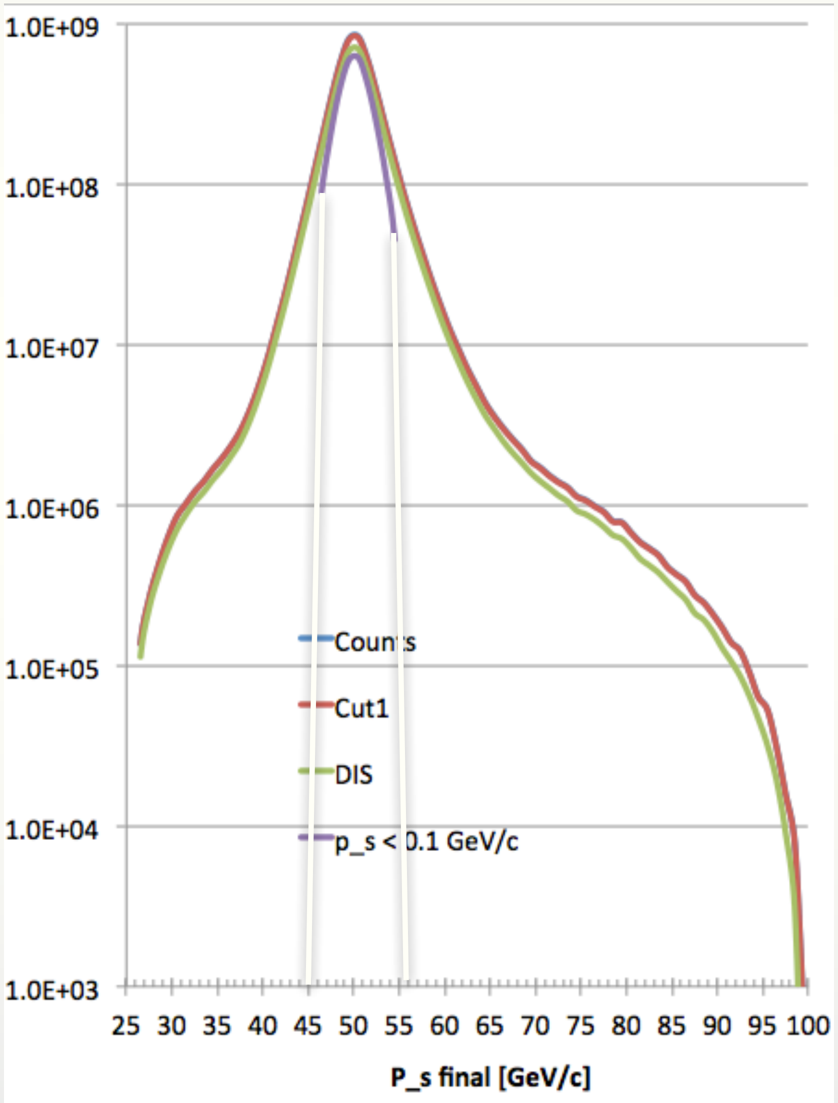
- The familiar (?) 1D world of Nucleon longitudinal structure:
  - Take a nucleon
  - Move it real fast along z
    $\Rightarrow$ light cone momentum
    $P_+ = P_0 + P_z$ (>>M)
  - Hit a "parton" (q, g,…) inside
  - Measure **its** l.c. momentum
    $p_+ = p_0 + p_z$ (m≈0)
  - $\Rightarrow$ Momentum Fraction $\xi = p_+ / P_+$ *)
  - In DIS: $\xi \approx (q_z - \nu)/M \approx x_{Bj} = Q^2/2M\nu$
    (in the target rest frame)
  - Probability: $F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)$
  - Because of spin-1/2: 2nd SF $F_2(x)$

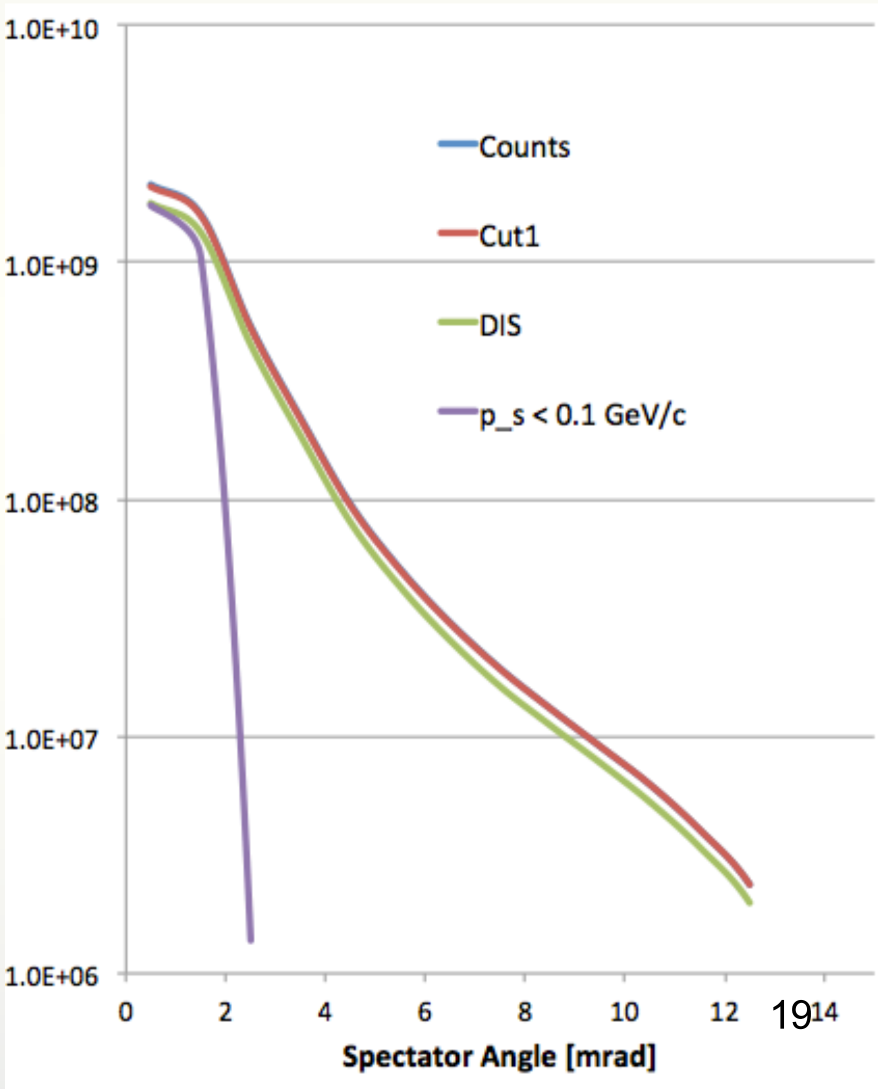


*) Advantage: Boost-independent

Spectator Tagging with the MEIC

Assume: 6 GeV e on 100 GeV D





Simple (Constituent) Quark Model

Flavor	Isospin I	I_3	Strangeness S	Charge Q	Baryon Number B
U	$1/2$	$+1/2$	0	$+2/3$	$1/3$
D	$1/2$	$-1/2$	0	$-1/3$	$1/3$
S	0	0	-1	$-1/3$	$1/3$

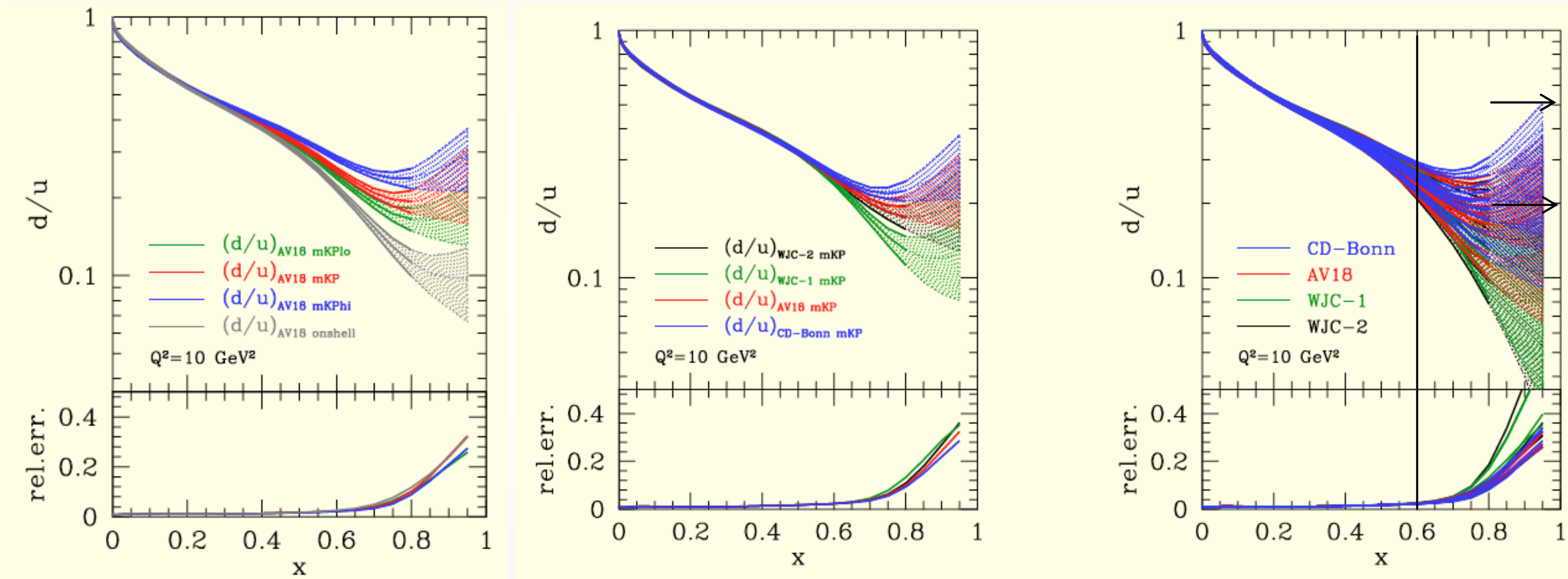
$$|\Delta^{++}\uparrow\rangle = |U\uparrow U\uparrow U\uparrow\rangle$$

$$|\Delta^{+}\uparrow\rangle = 1/\sqrt{3}\left(|U\uparrow U\uparrow D\uparrow\rangle + |U\uparrow D\uparrow U\uparrow\rangle + |D\uparrow U\uparrow U\uparrow\rangle\right)$$

The case of the proton is a bit more complicated, since the wave function cannot be symmetric in spin and flavor separately. The most intuitive way to derive the proton wave function is by observing that 2 of the 3 quarks are equal (U), and therefore their relative spin wave function should be symmetric also. This leads to the conclusion that the two U–quarks couple their spins to a total spin of one. Let's denote the case where this spin has a z-projection of $+1$ as $(UU\Uparrow) := |U\uparrow U\uparrow\rangle$, while the projection with $S_z = 0$ will be indicated by $(UU\Rightarrow) := 1/\sqrt{2}\left(|U\uparrow U\downarrow\rangle + |U\downarrow U\uparrow\rangle\right)$. We can now combine the spin 1/2 of the remaining D quark with the spin 1 of the UU pair in two ways to get total spin and projection 1/2; the proper way follows simply from insertion of the correct Clebsch-Gordon coefficients:

$$|P\uparrow\rangle = 1/\sqrt{3}\left(\sqrt{2}|(UU\Uparrow)D\downarrow\rangle - |(UU\Rightarrow)D\uparrow\rangle\right). \qquad (2)$$

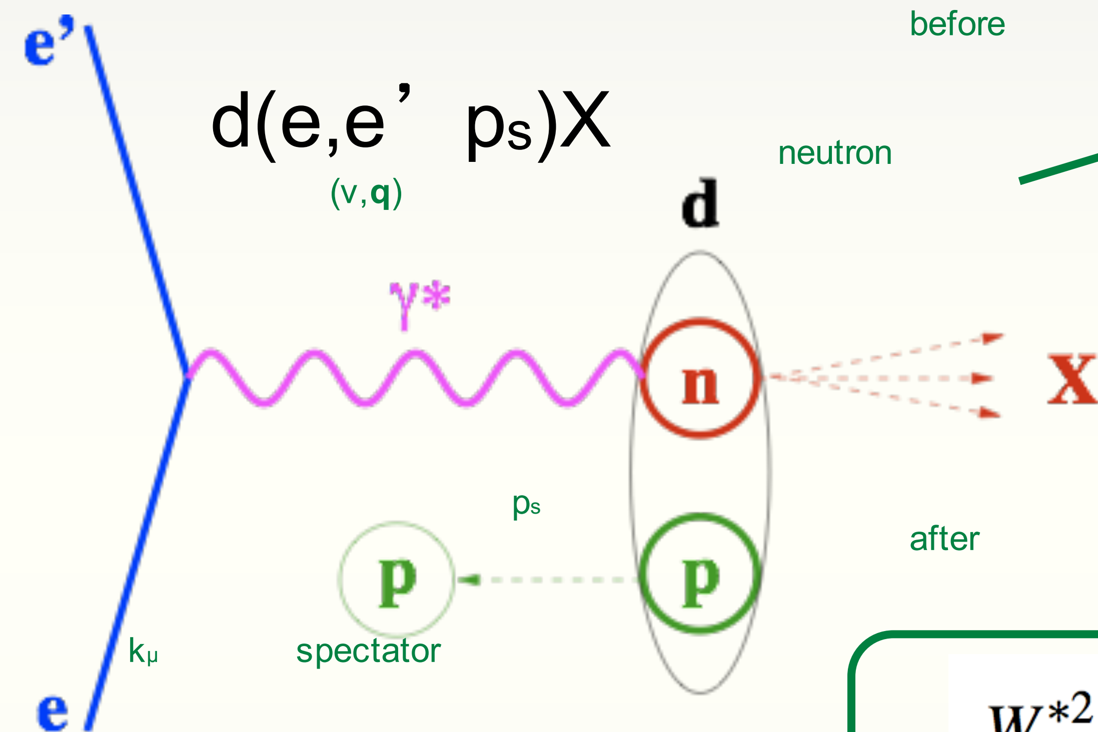
CTEQ6x (CJ) Fit of world data with relaxed cuts, TMC, HT, and various deuteron models



Dependence on off-shell prescription

Dependence on WF

Total (worst case) uncertainty



$$p_N^\mu = (M_d - E_s, -\vec{p}_s)$$

$$E_p + E_n = M_d$$

$$E^* = M_d - \sqrt{M_s^2 + p_s^2}$$

$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2}$$

- plane-wave impulse approximation
- backward-emitted p is spectator
- struck neutron is off-shell
- momenta are equal and opposite
- Lorentz invariants are corrected for initial neutron 4-momentum

$$W^{*2} \approx M^{*2} - Q^2 + 2M\nu\,(2 - \alpha_s)$$

$$\alpha_s = \frac{E_s - p_{s_{||}}}{M_s}$$

$$x^* = \frac{Q^2}{2p_N^\mu q^\mu} \approx \frac{Q^2}{2M\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

PWIA Spectator Formalism

$$\frac{d\sigma}{dx^* dQ^2} = \frac{4\pi\alpha_{\mathrm{EM}}^2}{x^* Q^4}\left[\frac{y^2}{2(1+R)} + (1-y) + \frac{M^{*2}x^{*2}y^2}{Q^2}\frac{1-R}{1+R}\right]F_2(x^*, \alpha_s, p_T, Q^2) \times S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2 p_T,$$

Cross Section

Off-Shell F_2

$R=\sigma_L/\sigma_T$

Light Cone

Spectral Function

Nonrelativistic w.f.

$$P(\vec{p}_s) = J|\psi_{\mathrm{NR}}(p_s)|^2$$

$$J = 1 + \frac{p_{s_{||}}}{E_n^*} = \frac{(2-\alpha_s)M_d}{2(M_d - E_s)}$$

$$S(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2 p_T = P(\vec{p}_s)d^3 p_s$$

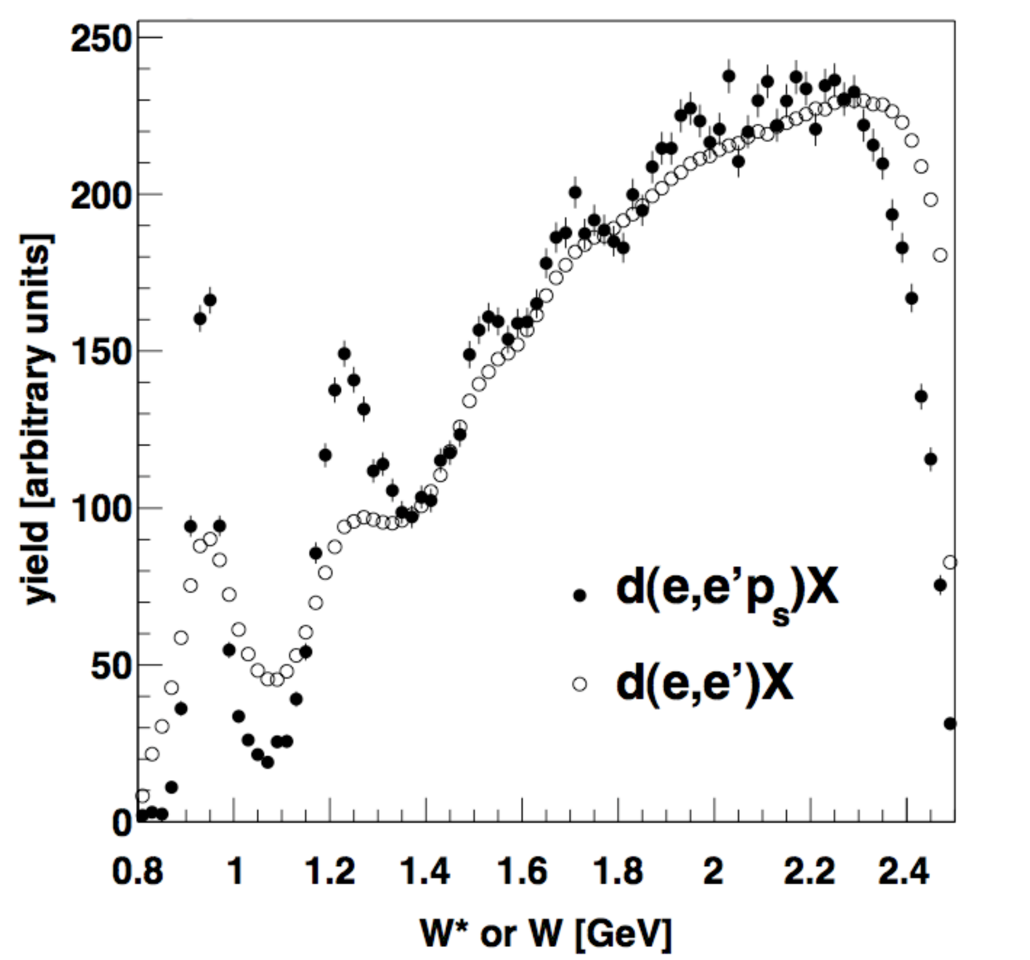
$$S^{\mathrm{LC}}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2 p_T = |\psi_{\mathrm{NR}}(|\vec{k}|^2)|^2 d^3 k$$

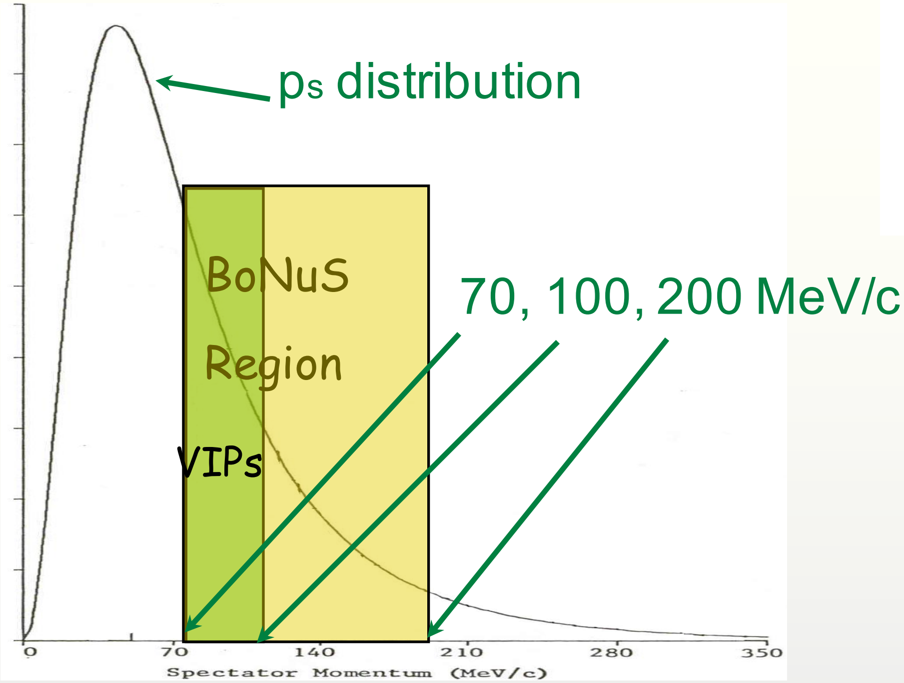
$$|\vec{k}| = \sqrt{\frac{M^2 + p_T^2}{\alpha_s(2-\alpha_s)} - M^2} \qquad \alpha_s = 1 - \frac{k_{||}}{\sqrt{M^2 + \vec{k}^2}}$$

$$k_0 = \sqrt{M^2 + \vec{k}^2} \qquad \vec{p}_T = \vec{k}_T$$

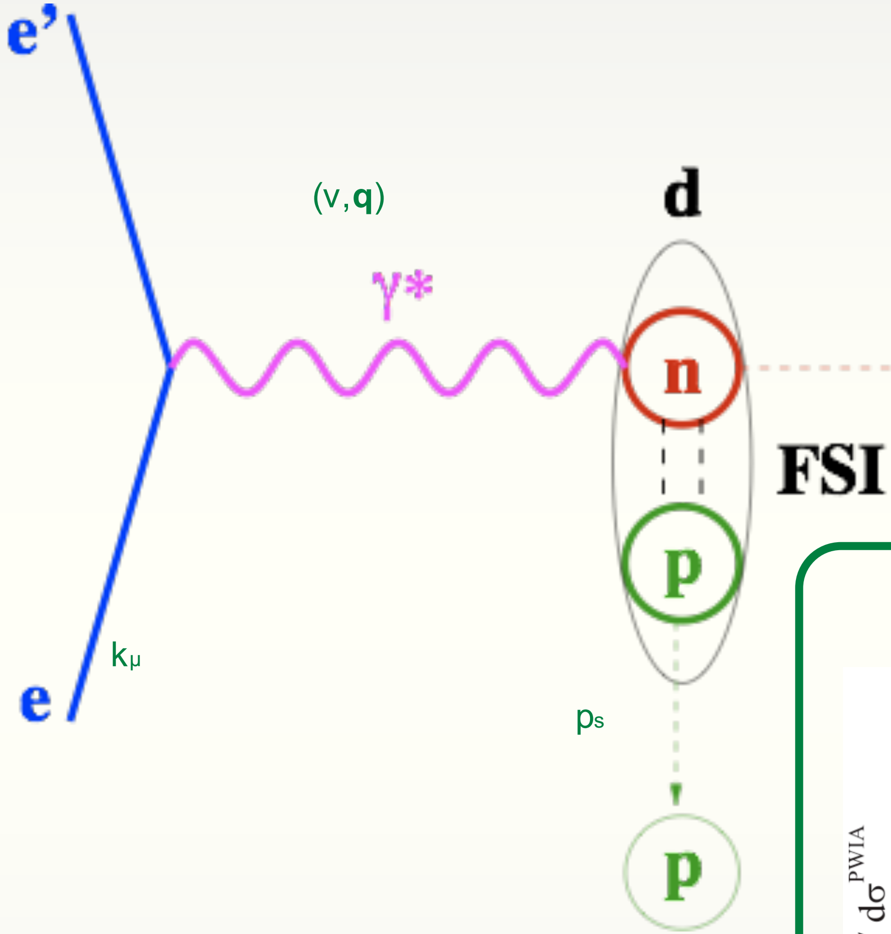
$$\int\int\int S^{\mathrm{LC}}(\alpha_s, p_T)\frac{d\alpha_s}{\alpha_s}d^2 p_T = 1$$

- Very Important Protons $70<p_s<100$ MeV/c
- Corrections make resonances stand out
- F_2^n/F_2^p can be measured at high x*



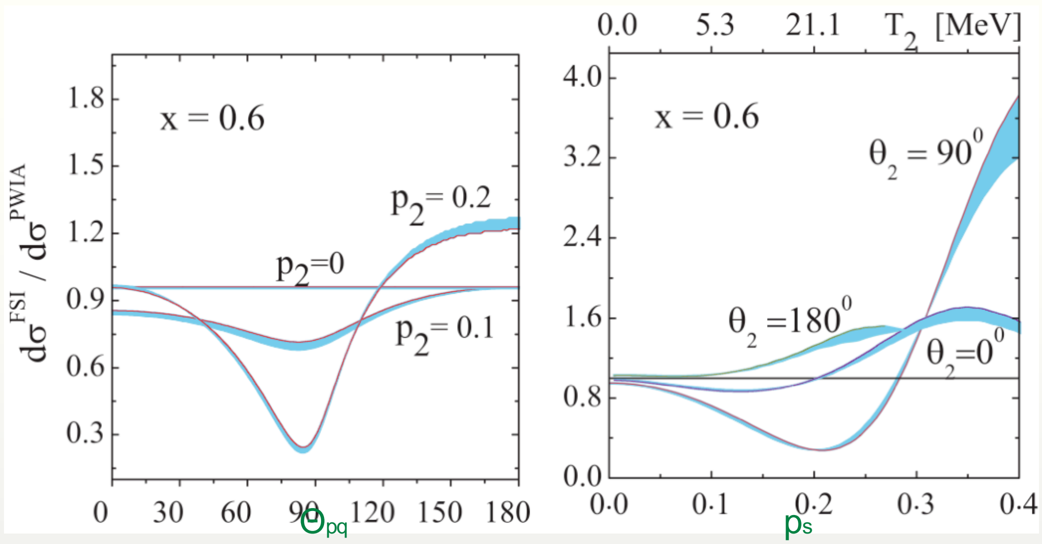


Final State Interactions



- struck neutron can interact with the spectator proton
- proton momentum is enhanced
- FSIs are small at low p_s and large Θ_{pq}

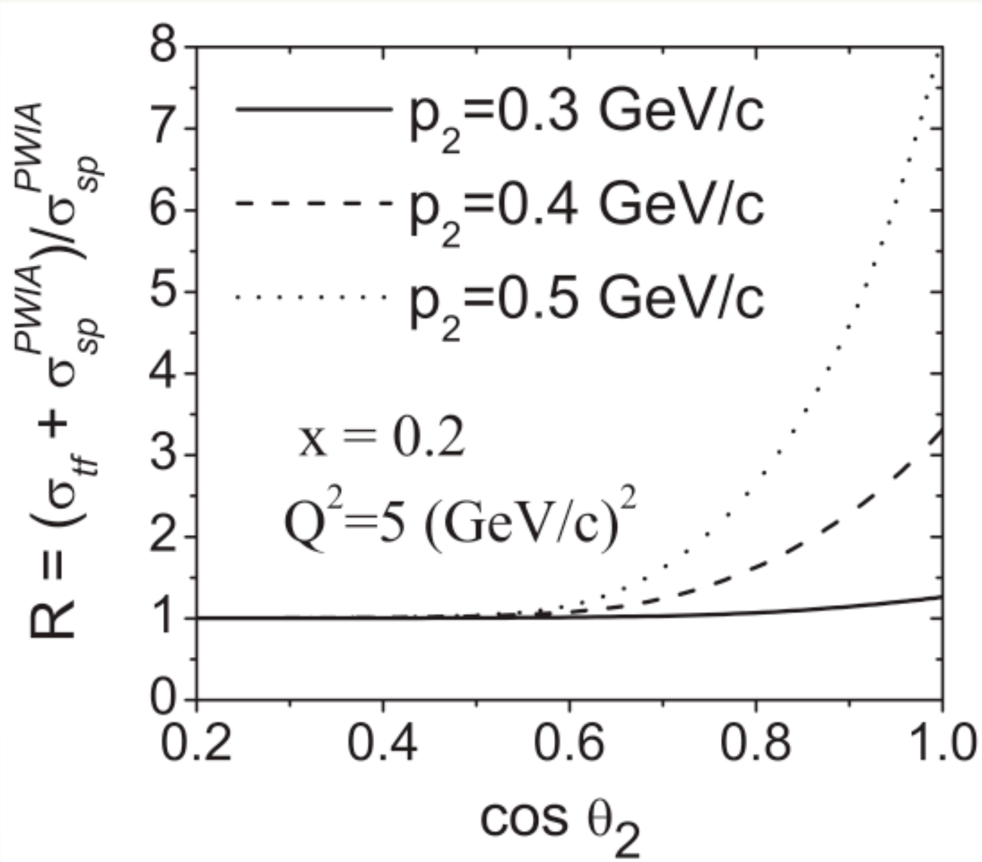
Palli et al, PRC80(09)054610



- several groups have calculated FSIs
- $\Theta_{pq} > 110^o$ minimizes FSIs

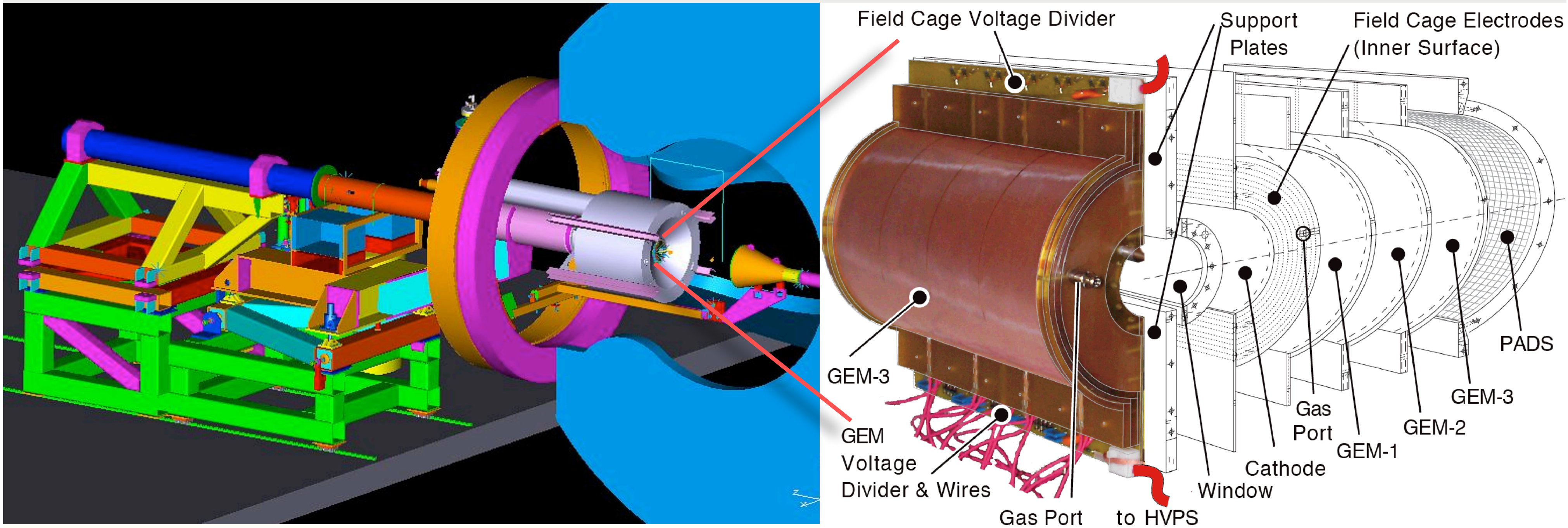
Target Fragmentation

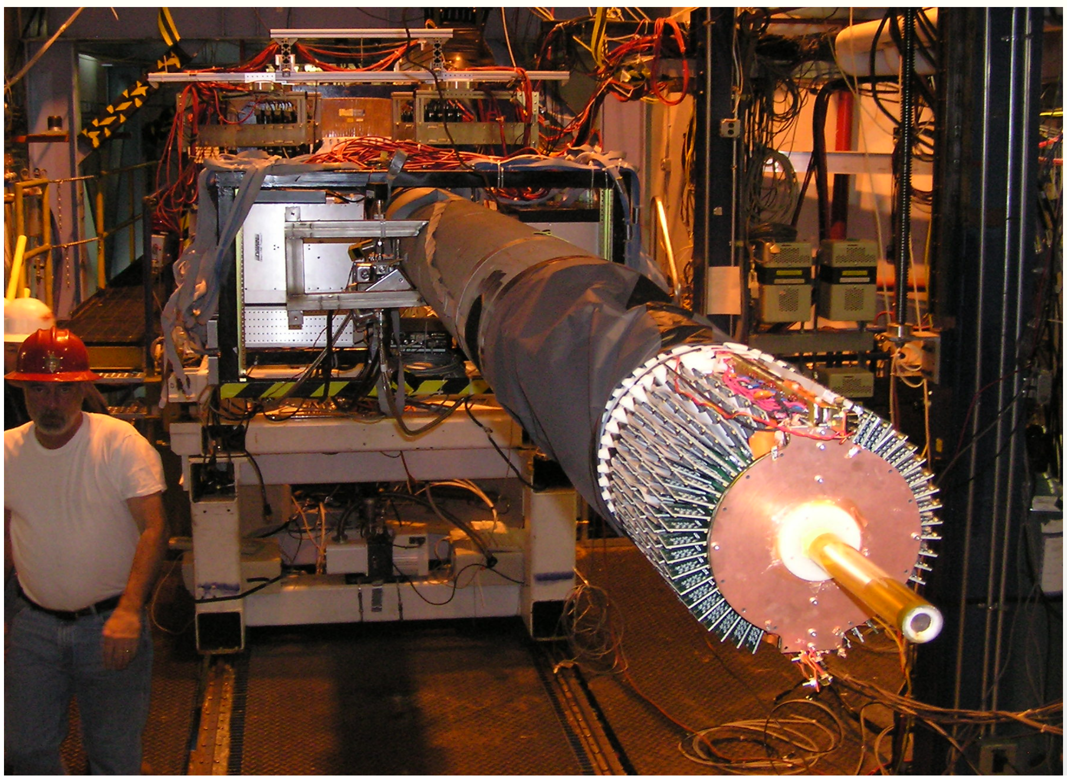
Palli et al, PRC80(09)054610

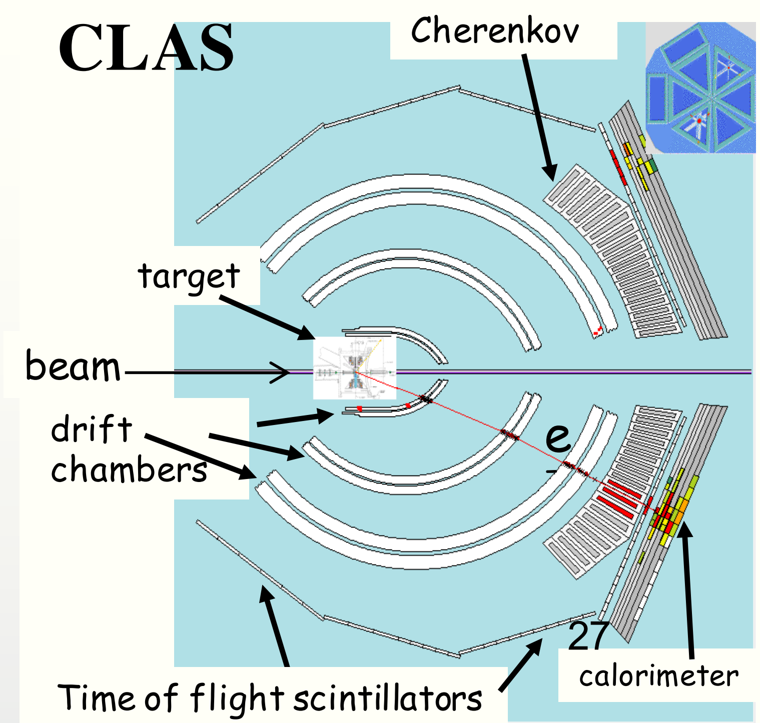


cos Θ_{pq}

- target fragmentation enhances the proton yield only at forward angles (cos Θ_{pq} >0.6)
- this can be ignored

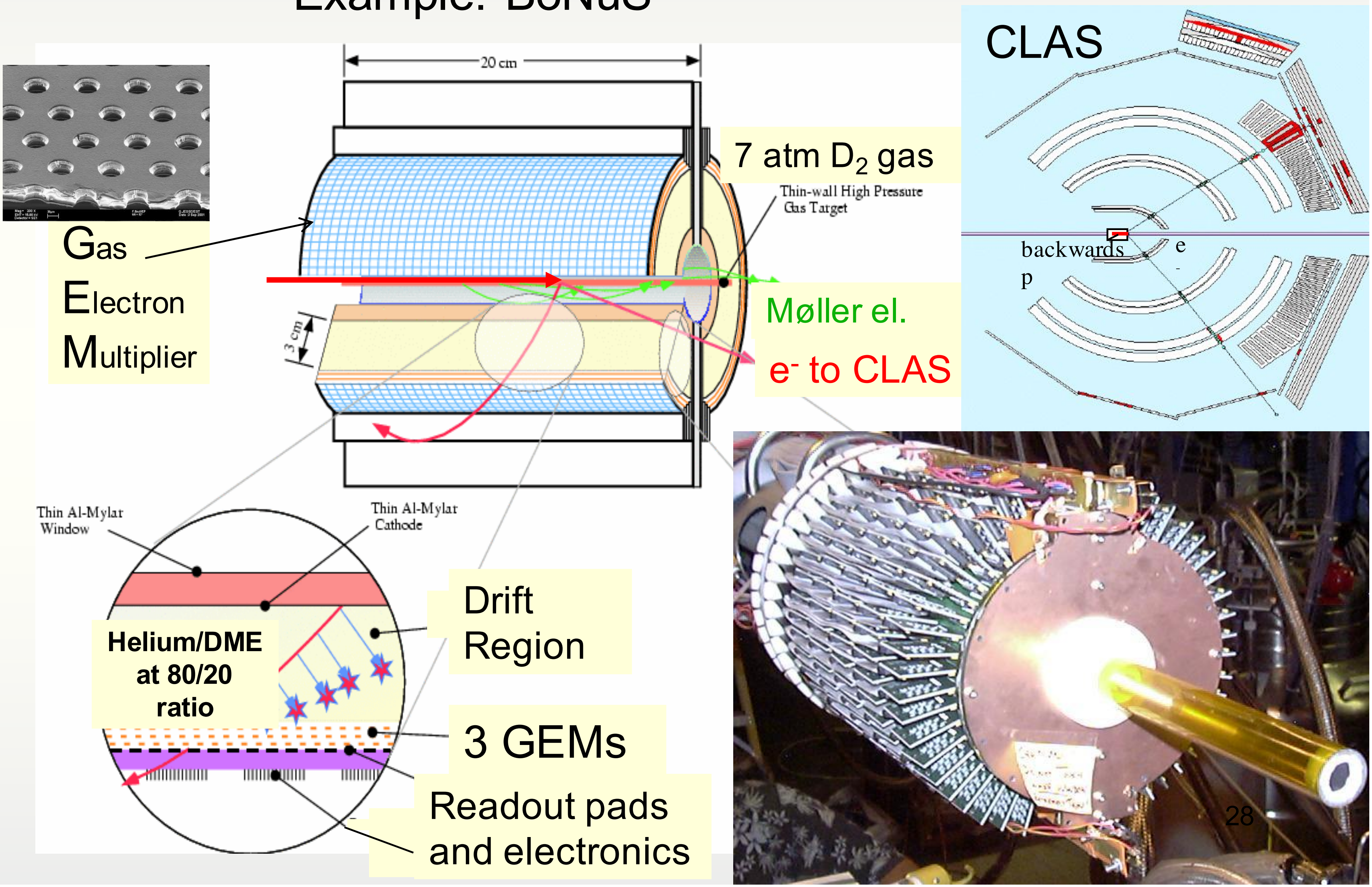

Field Cage Voltage Divider
Support Plates
Field Cage Electrodes (Inner Surface)
PADS
GEM-3
GEM-3
GEM-2
GEM-1
Gas Port
Cathode
Window
GEM Voltage Divider & Wires
Gas Port
to HVPS



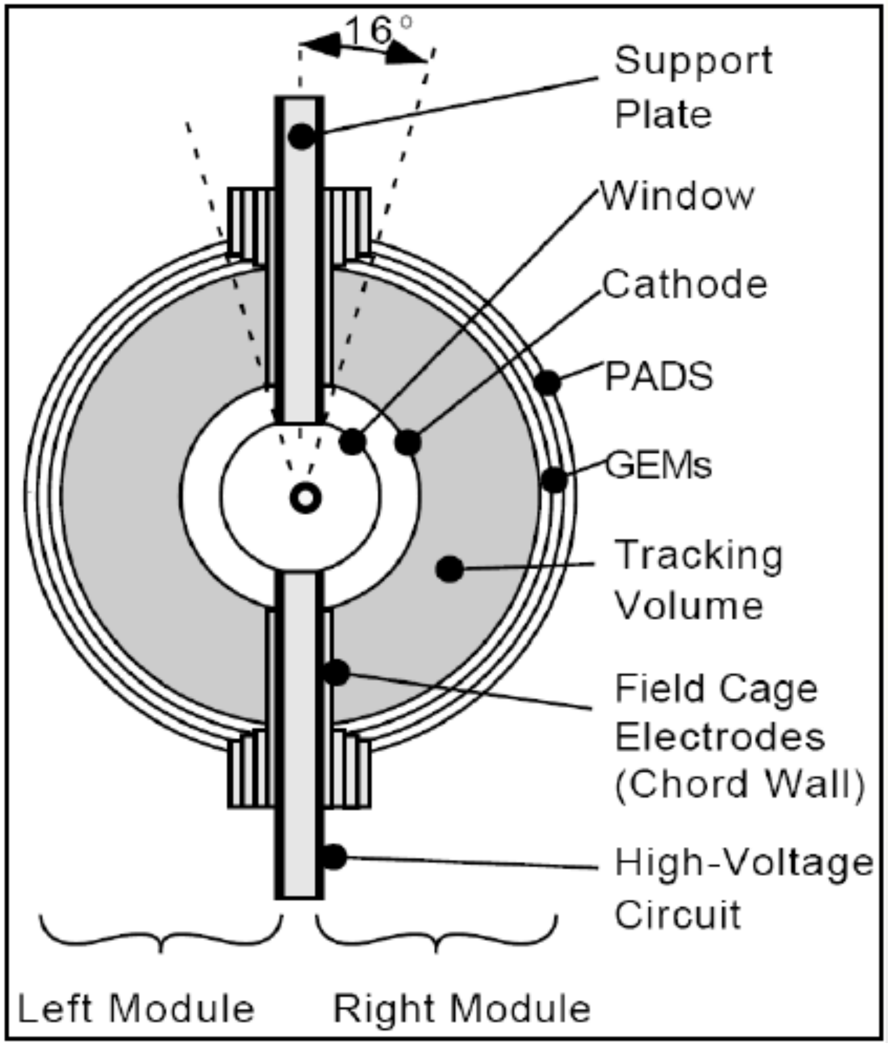

CLAS
Cherenkov
target
beam
drift chambers
e-
calorimeter
Time of flight scintillators

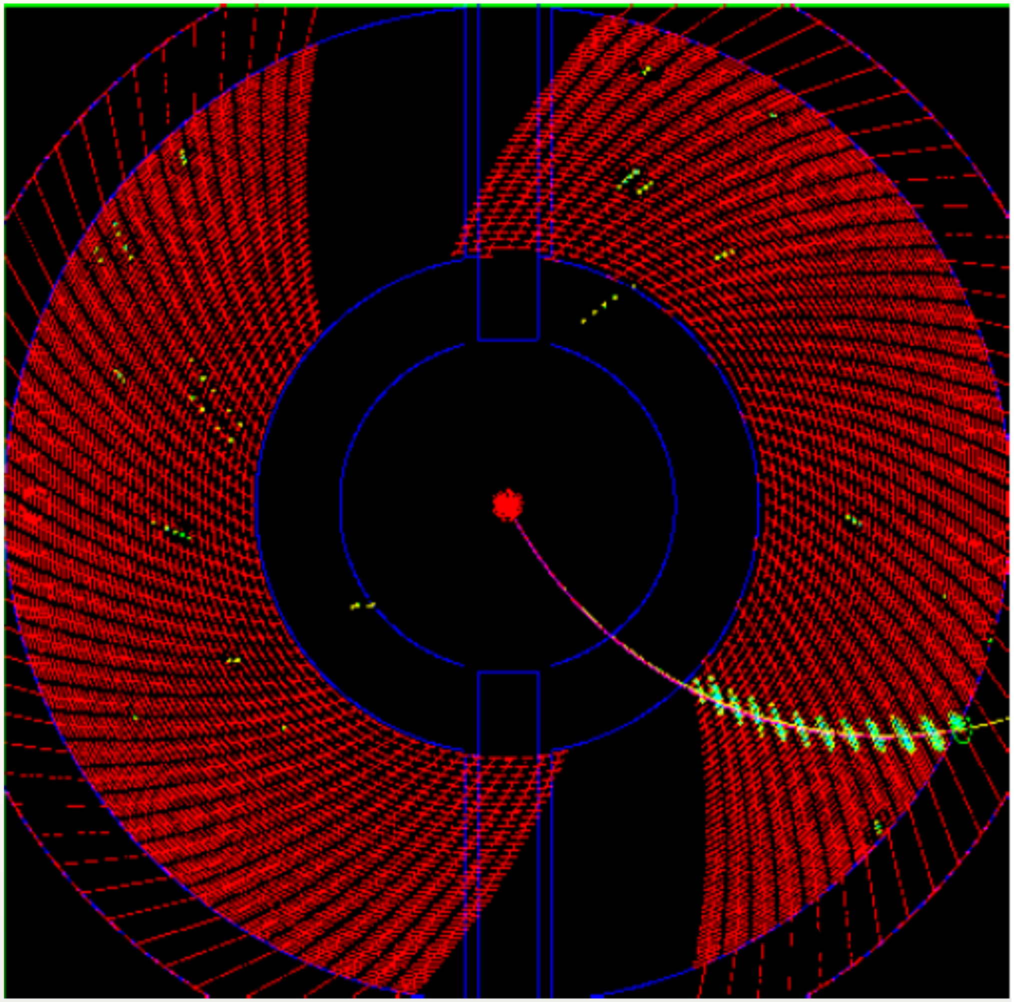
Spectator Tagging

Example: BoNuS

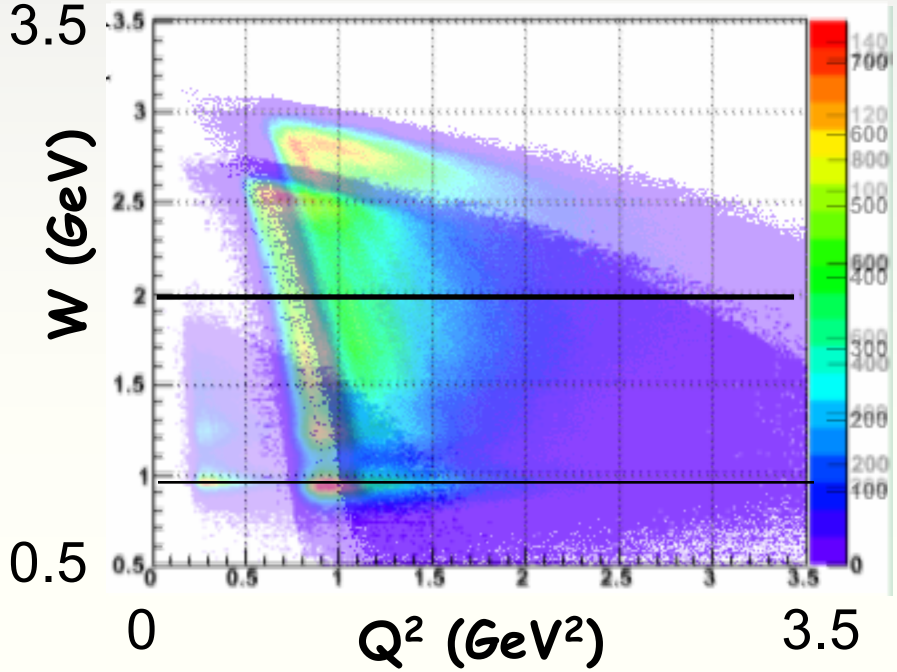


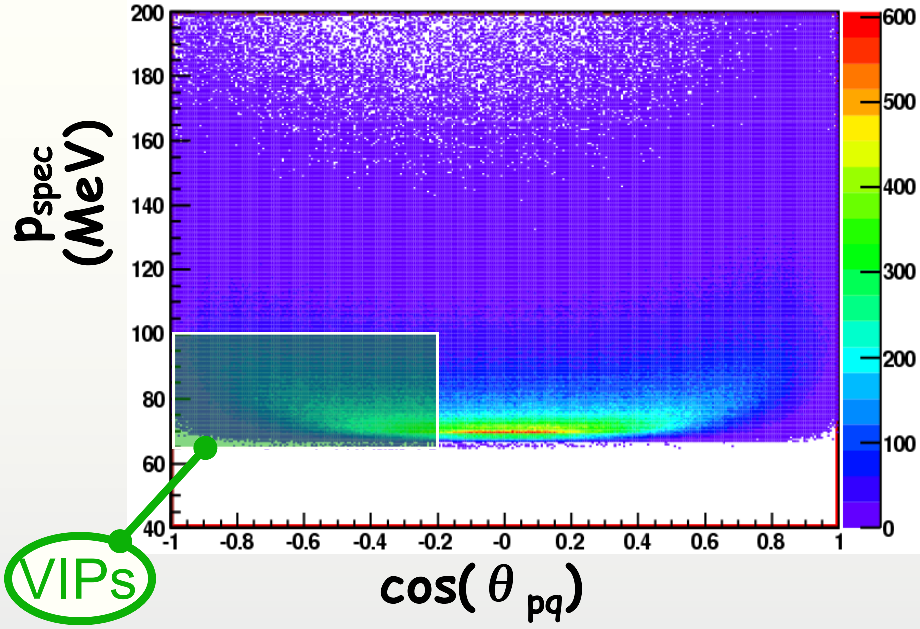
RTPC Cross Section





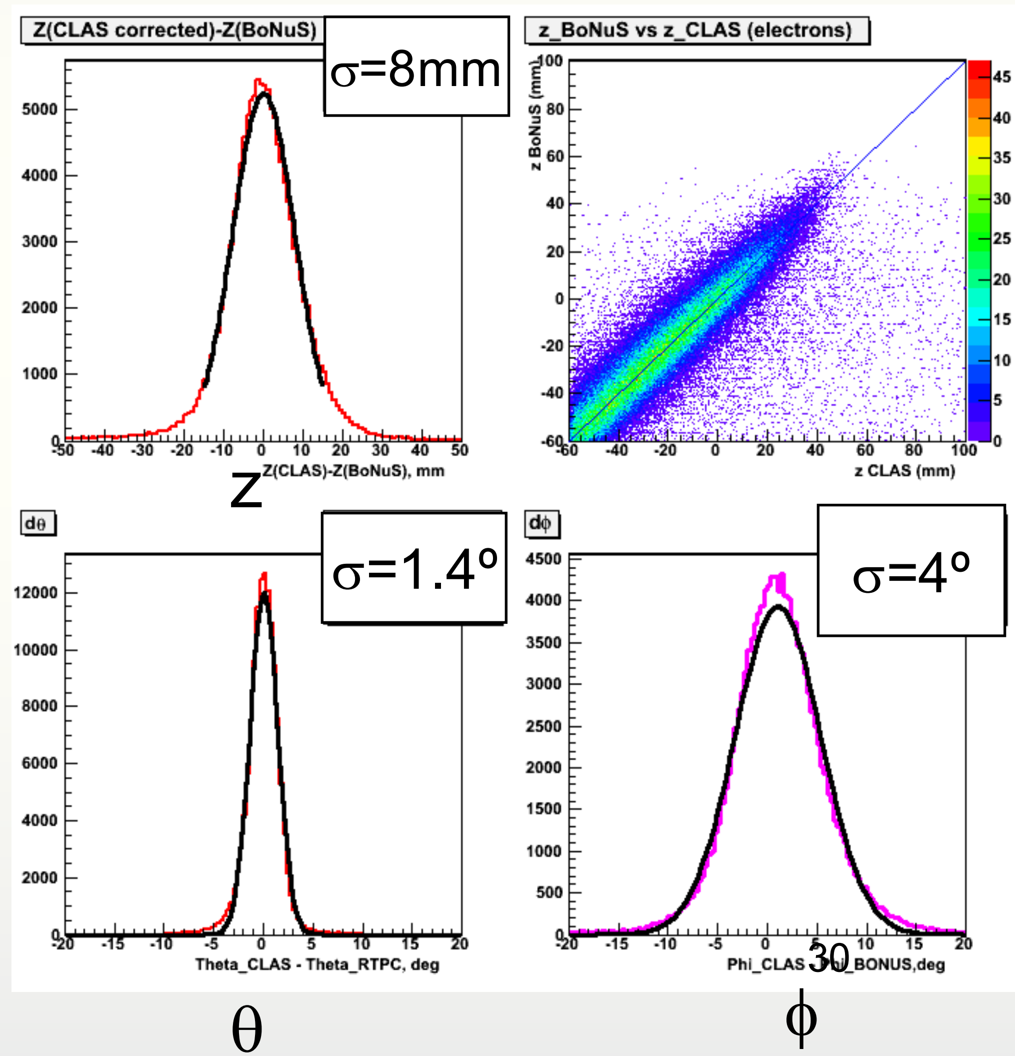
Kinematic Coverage - 2.1, 4.2 & 5.3 GeV



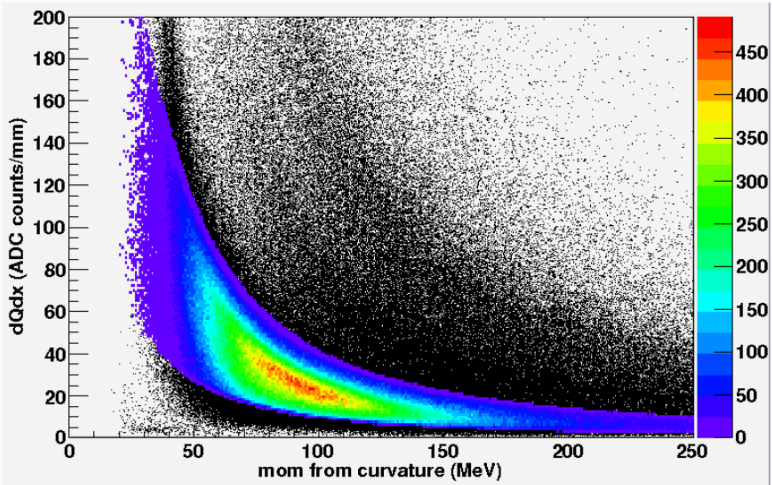


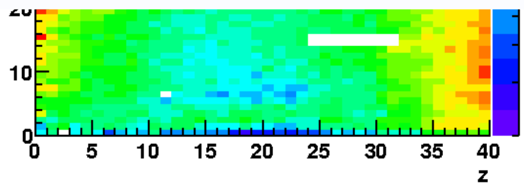
RTPC Performance

e^- reconstructed in CLAS & RTPC



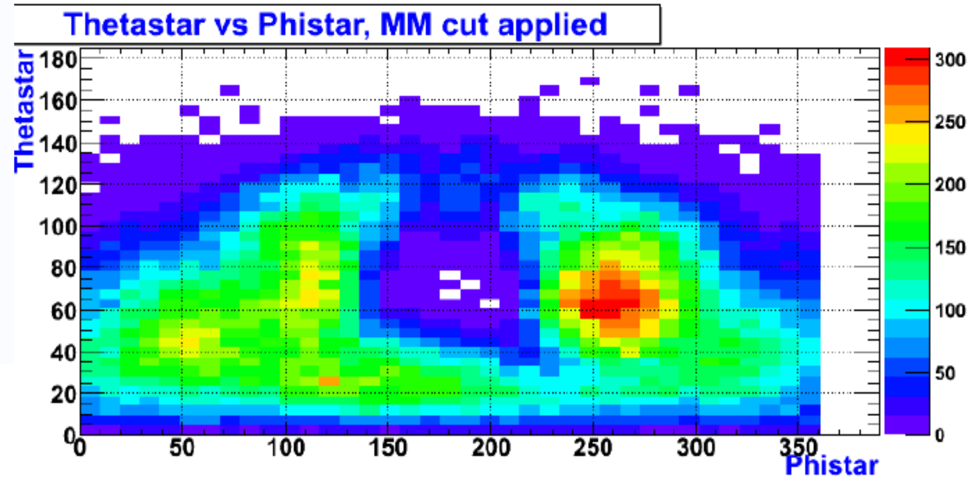
Particle ID (after gain calibration of each channel)

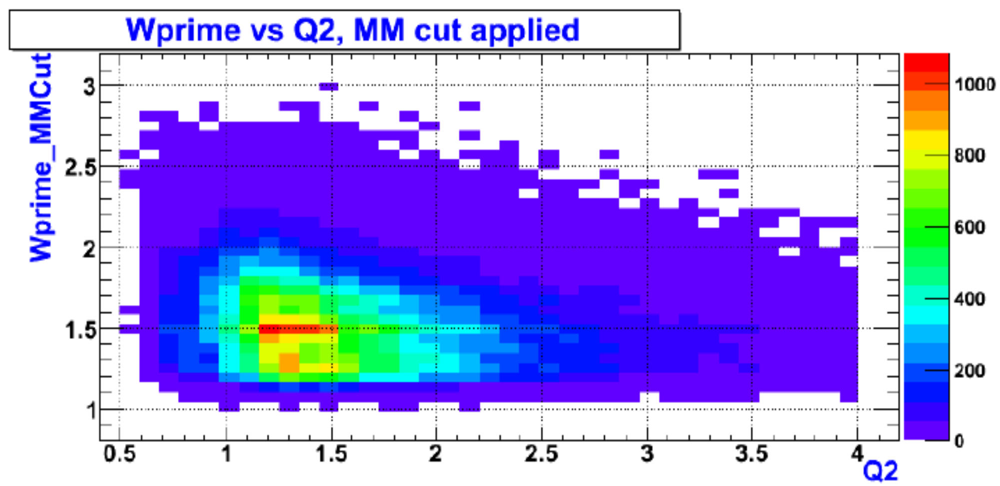




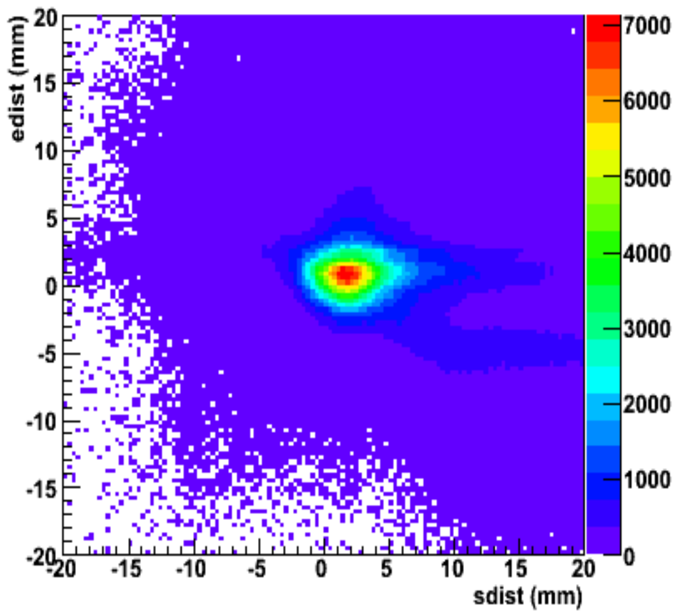
(colder) than
average pads

inematics coverage, $D(e,e'\pi^{-}p)p$, E = 5.3 GeV





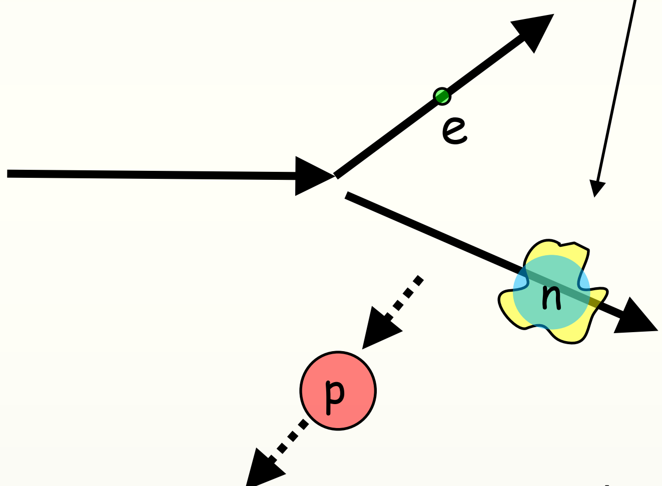
Out-of-time track suppression



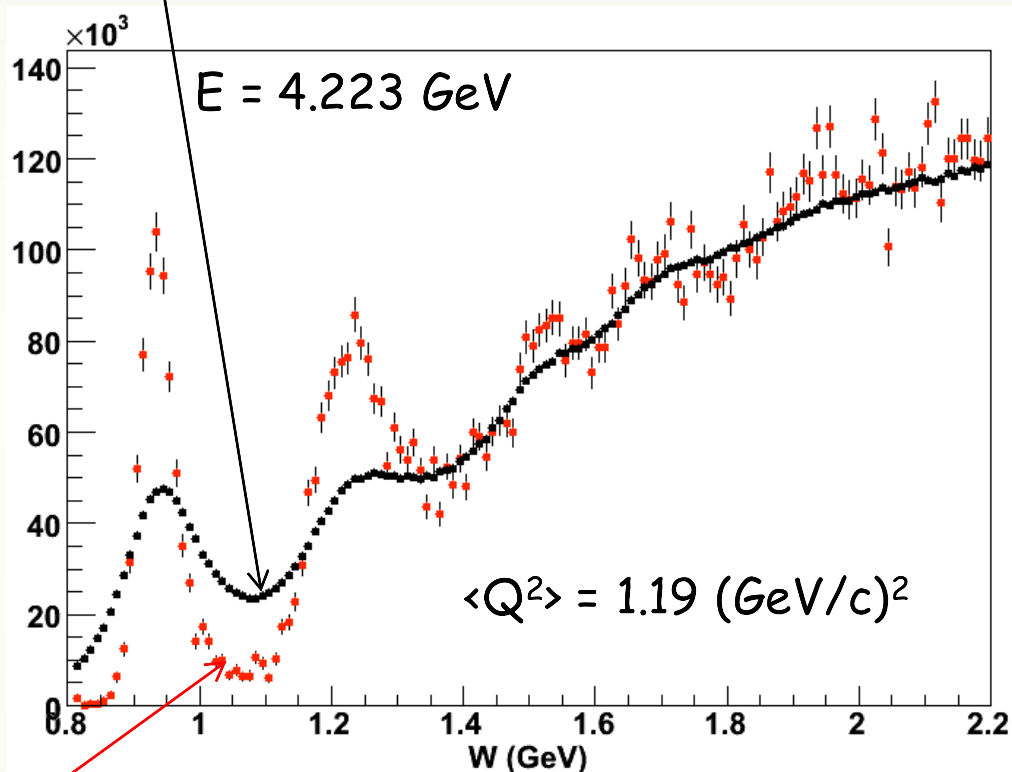
Minimizing Nuclear Uncertainties: "Spectator Tagging"

$$W^2 = M^2 + 2M\nu - Q^2$$

$$p_n = \left(M_D - E_S, -\vec{p}_S\right);$$
$$\alpha_n = 2 - \alpha_S$$



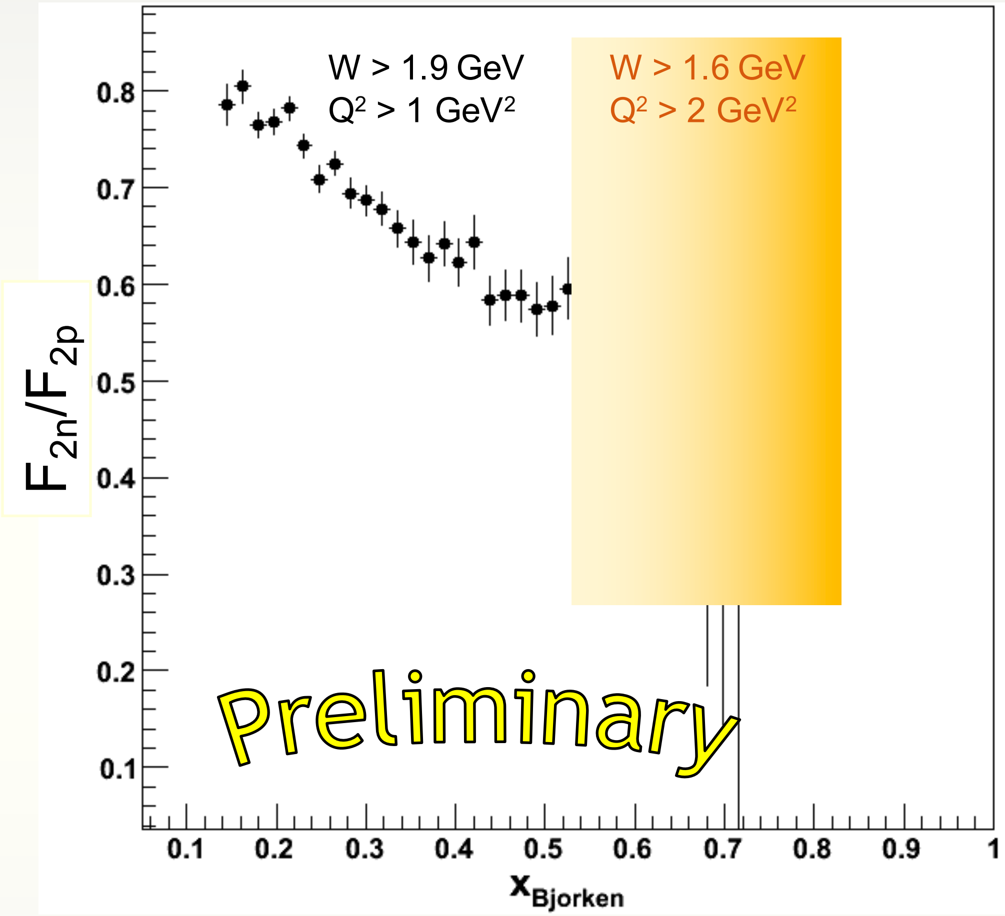
$$p_S = \left(E_S, \vec{p}_S\right); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D / 2}$$



$$W^{*2} = \left(p_n + q\right)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$
$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

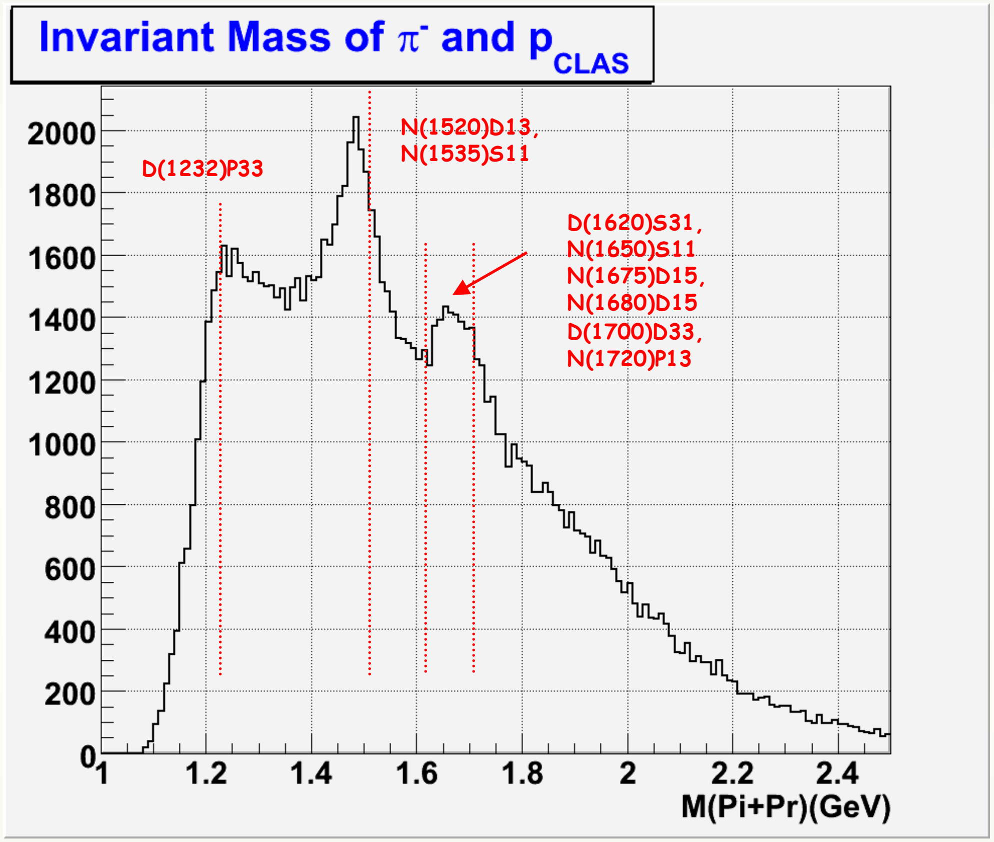
$$x^* = \frac{Q^2}{2p_n^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2 - \alpha_S)}$$

Preliminary Results from BoNuS



Baryonic Resonances, $D(e,e'\pi\text{-}p)p$

E = 5.26 GeV, Accepance and momentum not corrected yet

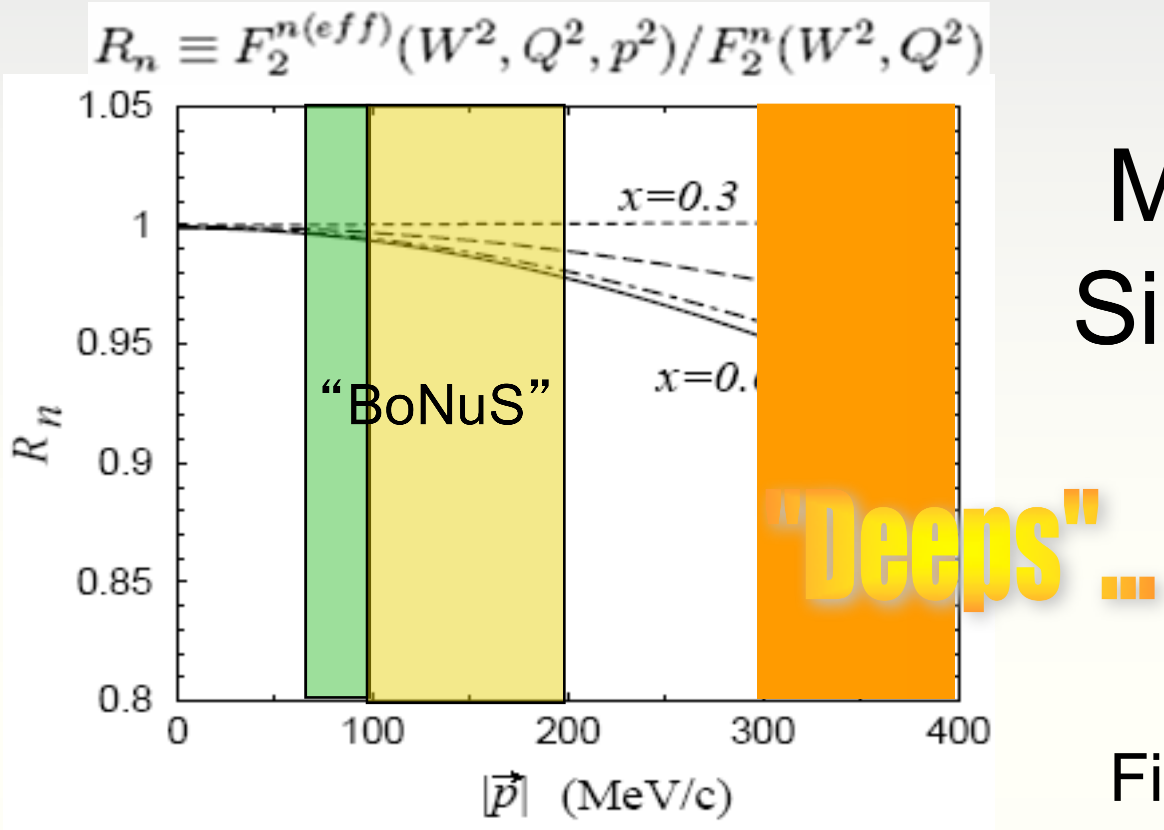


- Measured tagged n / inclusive d
- Multiplied with F_{2d}/F_{2p}
- Normalized at small *x*
- Acceptance corrections underway

$D(e, e'\, \pi^-\, p_{CLAS})p_s$ +

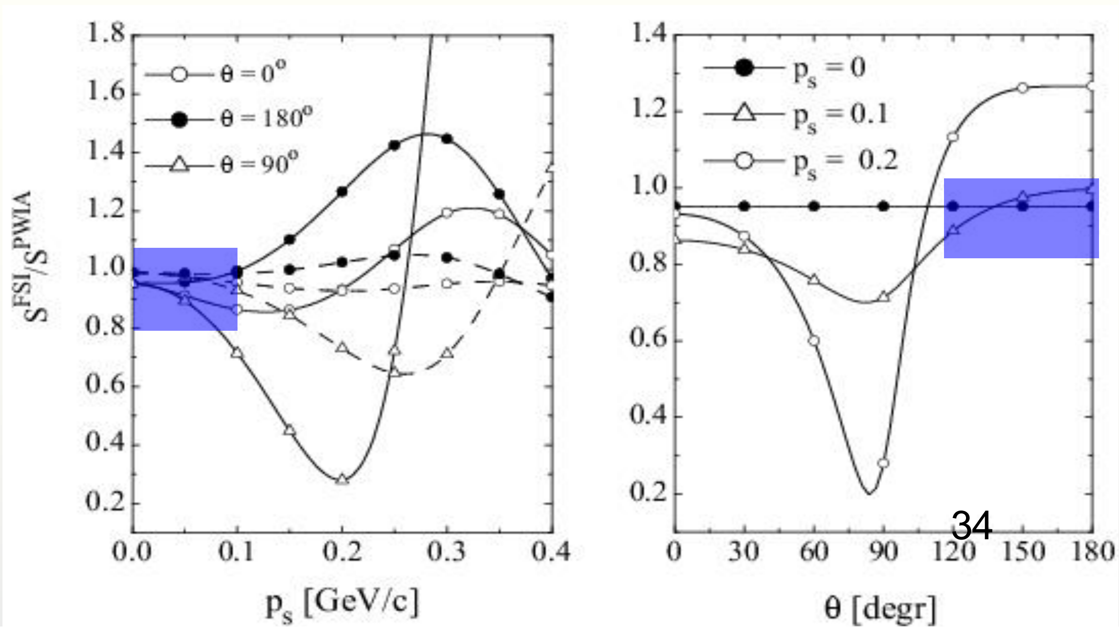
$D(e, e'\, \pi^-\, p_{RTPC})p_{decay}$

Modifications to Simple Spectator Picture



Binding Effects ↑

Final State Interactions ↓

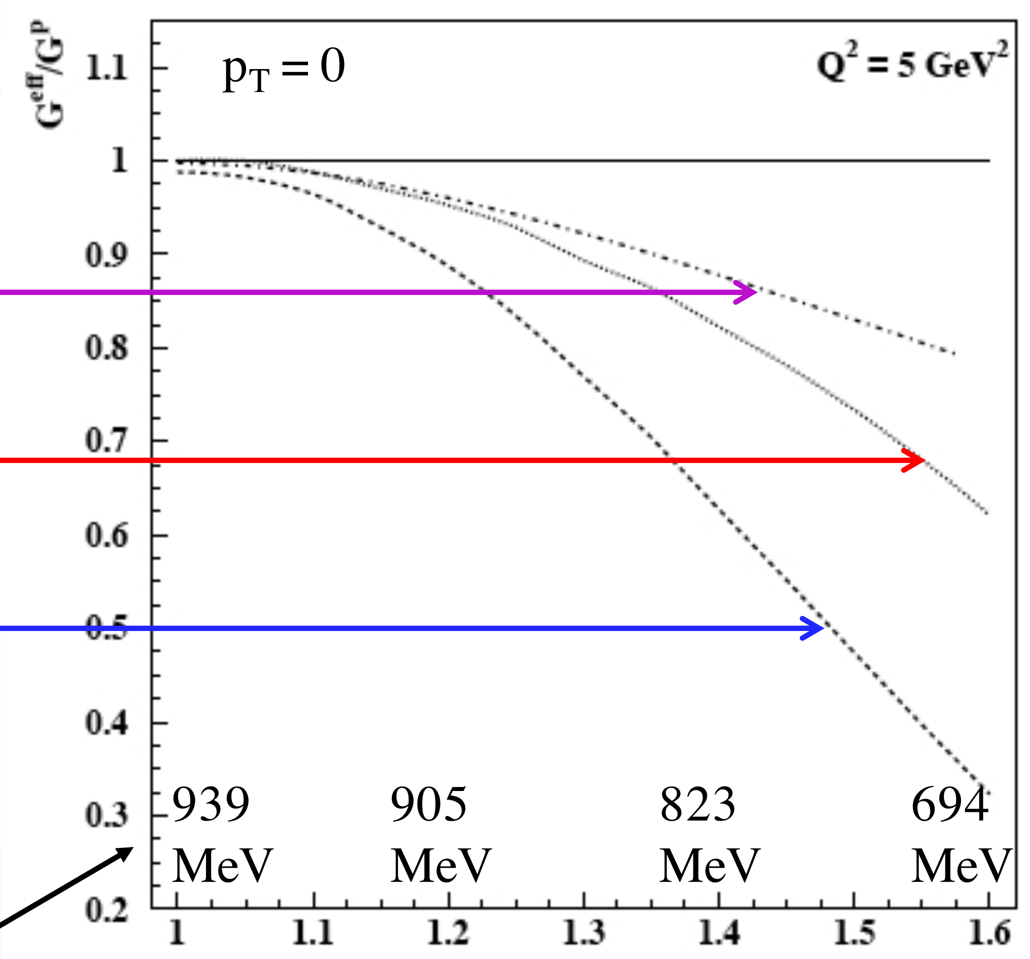


Ciofi degli Atti and Kopeliovich, Eur. Phys. J. A17(2003)133

Deviations from free structure function:

Off-shell Effects [should depend on α (p_s), x, Q^2]

$$\frac{F_{2N}^{eff}(x=0.6,Q^2,\alpha)}{F_{2N}^{eff}(x=0.2,Q^2,\alpha)}$$



P_s = 0 0.09 0.17 0.25 0.32 0.39 GeV/c

Modification of the off-shell scattering amplitude (Thomas, Melnitchouk et al.)

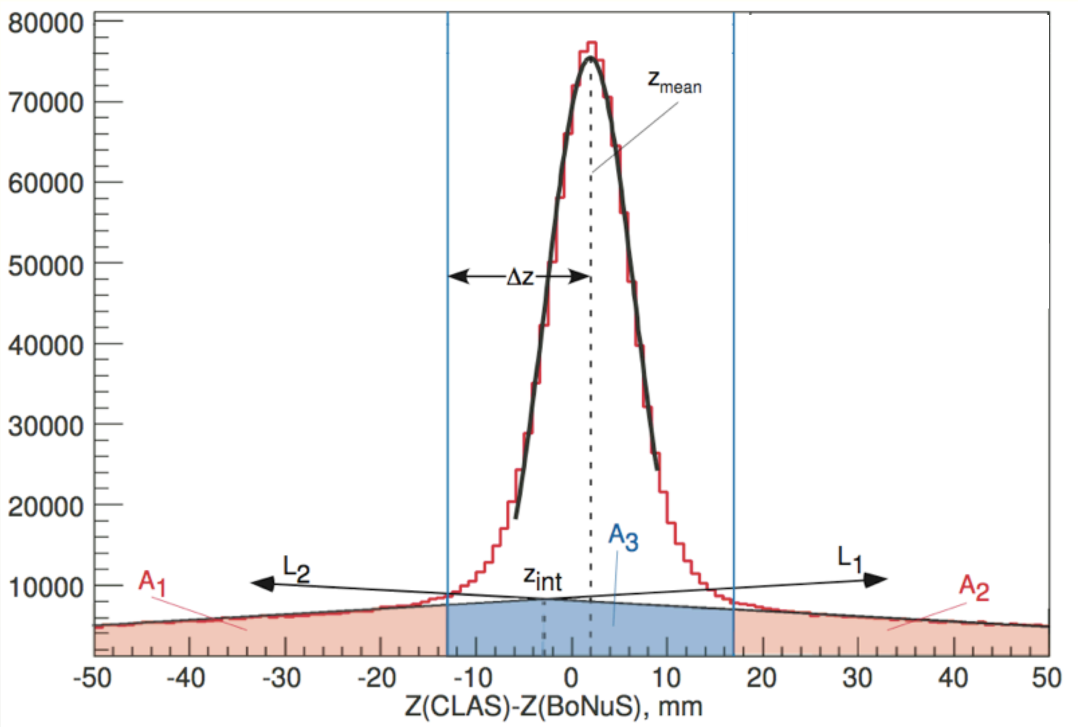
Color delocalization Close et al.

Suppression of "point-like configurations" Frankfurt, Strikman et al.

… plus 6-quark bags, ΔΔ, MEC…

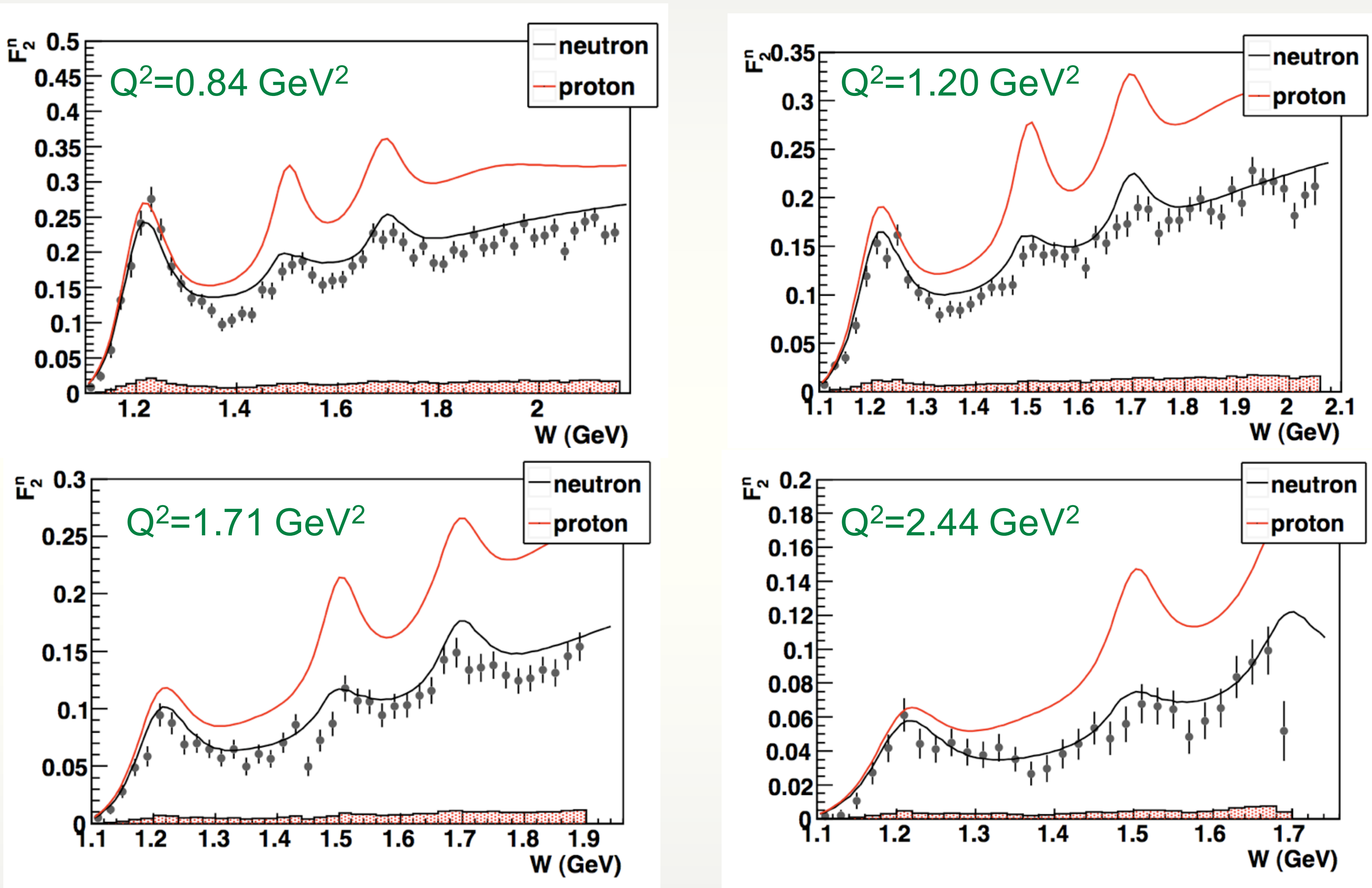
"Off-shell" mass of the nucleon M^*

- The Ratio Method
  - measure tagged counts divided by inclusive counts
  - correct this ratio for backgrounds
  - one scale factor gives F_2^n/F_2^d
- The Monte Carlo Method
  - measure tagged counts
  - divide by spectator model Monte Carlo results
  - multiply by F_2^n used in the model
- The two methods have different systematic errors, but give very similar results.



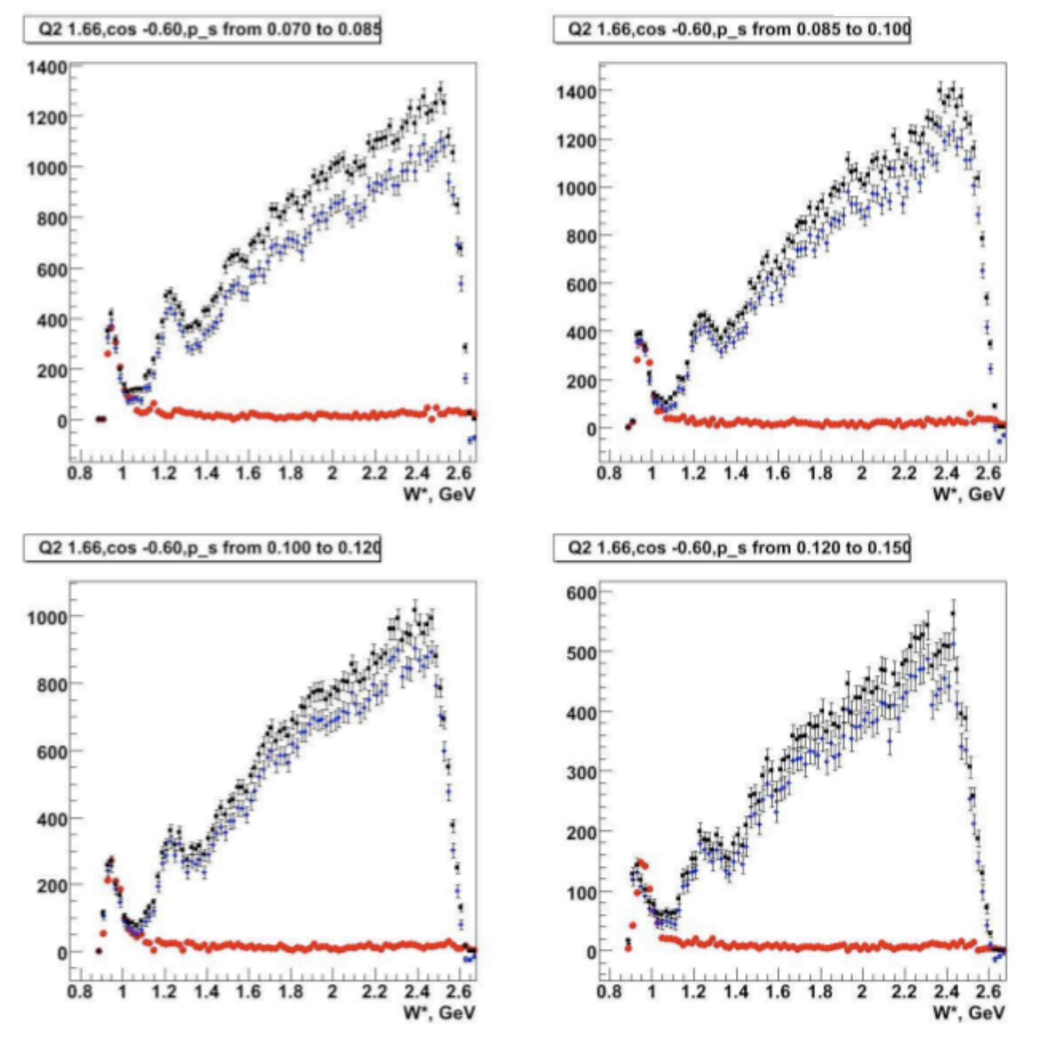
- Z is the position along the beam direction
- Tracking of the electron gives Z(CLAS)
- Tracking of the spectator proton gives Z(BoNuS)
- ΔZ=Z(CLAS)-Z(BoNuS) shows a coincidence peak and a triangular background
- Fits to the triangular background allows us to measure backgrounds underneath the peak
- Blue area = R_{bg} x Pink area
- R_{bg} is independent of kinematics

BoNuS F_2^n



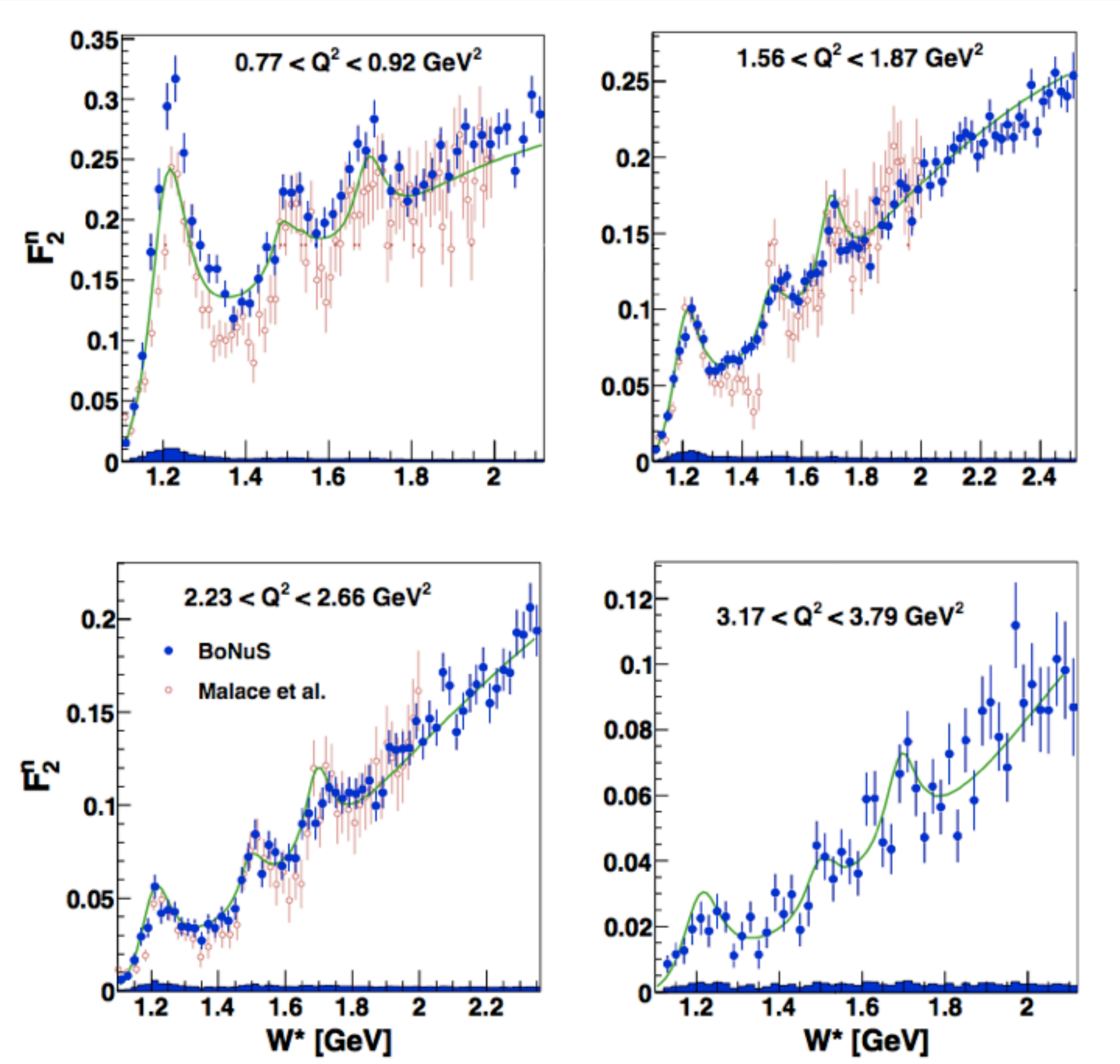
4 of 16 spectra: $0.8 < Q^2 < 4.5$; E_{beam} = 4.2 & 5.3 GeV; Bosted/Christy world fits

$$R(data/MC) = \frac{F_{2n}^{eff}(W^*, Q^2, \vec{p_s})}{F_{2n}^{model}(W, Q^2)}$$



Left: Black=raw tagged data; blue=accidental subtracted data; red=elastic and radiative tail

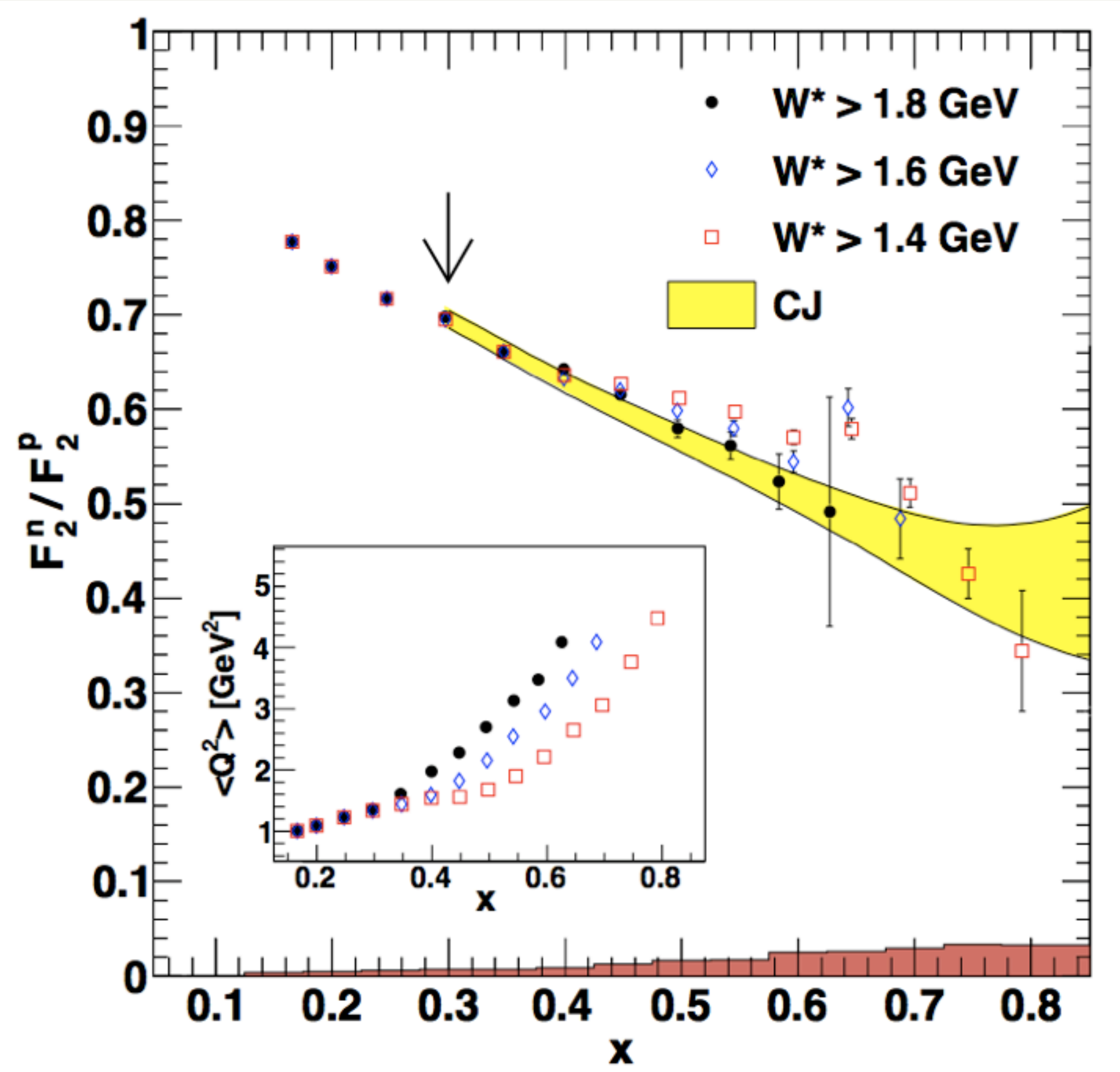
Final 4 GeV Data F_{2n}



BoNuS data compared to a state of the art nuclear physics extraction of neutron structure functions from deuterium (red points, Malace, et al.)

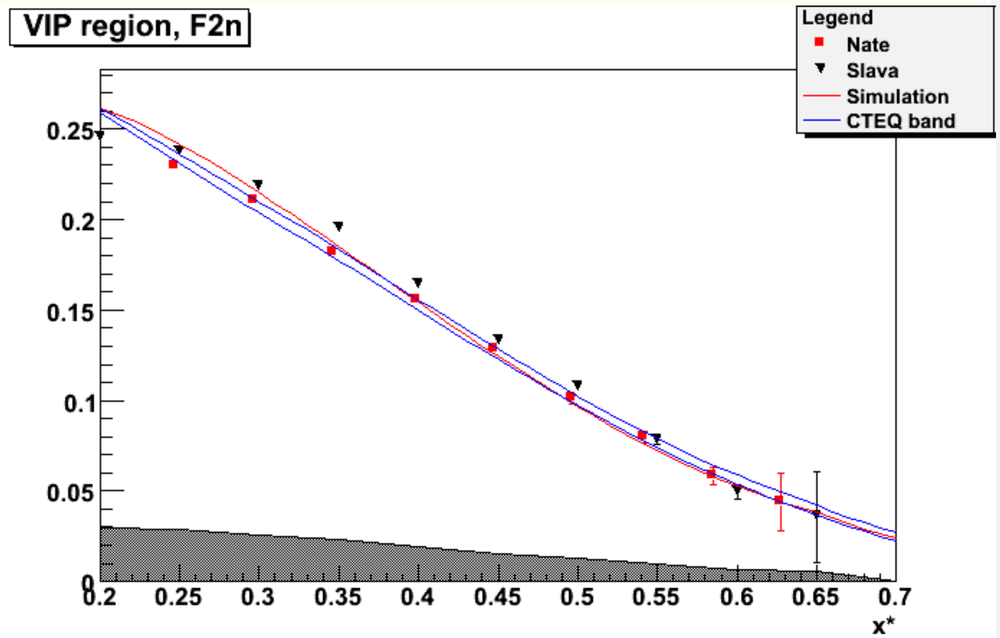
and a model (green line by Christy et al.)

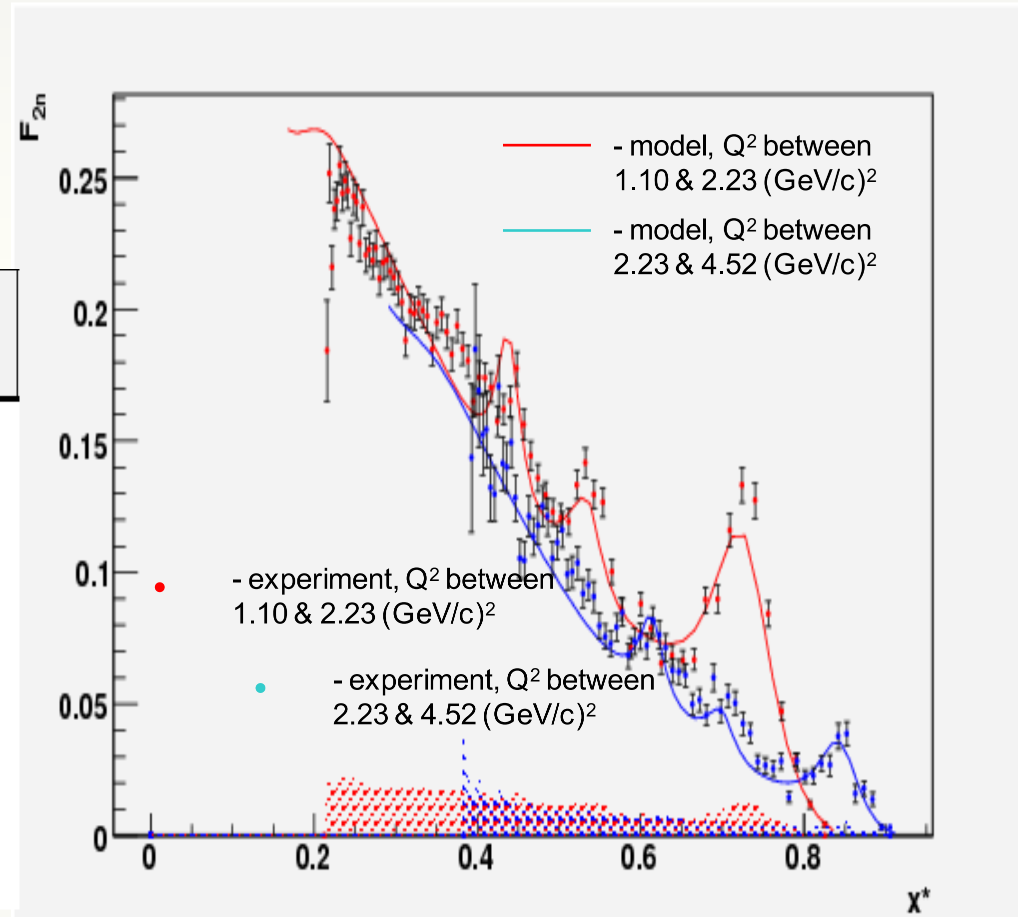
BoNuS F_2^n/F_2^p



- F_2^n/F_2^n vs. x
- Curves are CETQ error bands
- CETQ cuts off at low x because Q^2 is too low
- Lower cuts in W* imply higher x but the inclusion of resonance contributions.
- Results are consistent with CETQ trends at high x.

Results from BoNuS (iii)

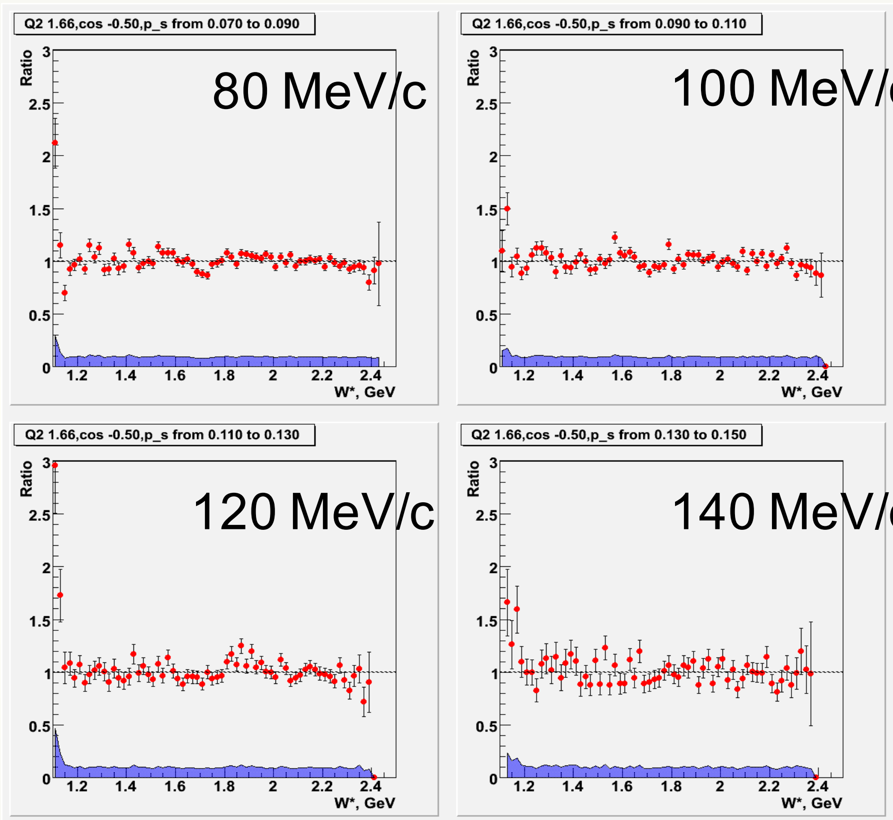




5 GeV Data

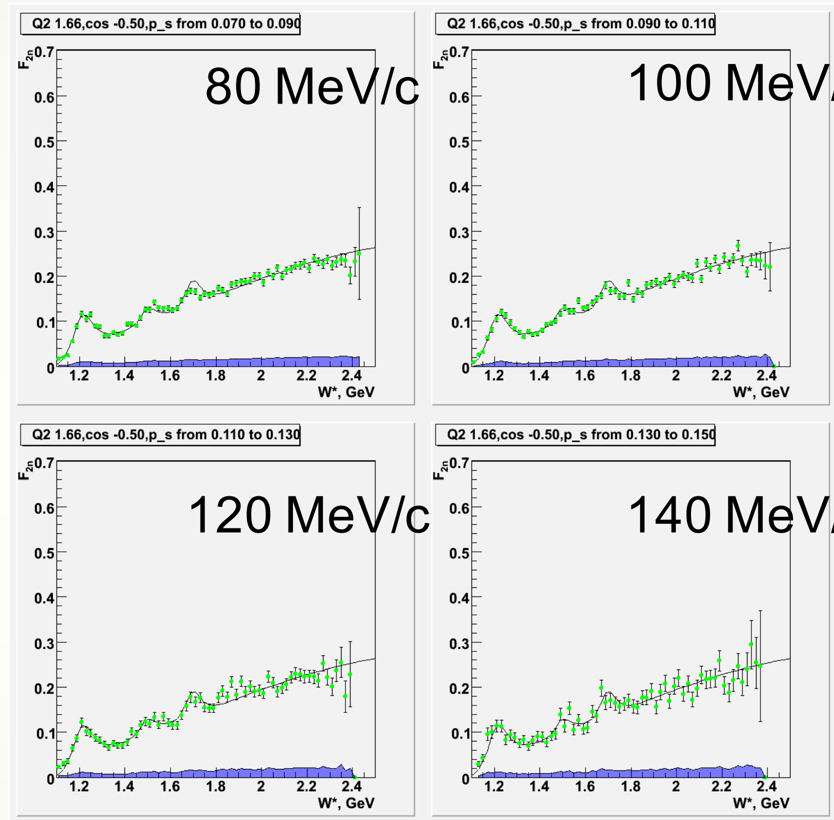
Results from BoNuS (iv)

Testing the Spectator Assumption - dependence on p_s



W* [GeV]

Ratio Data/Model



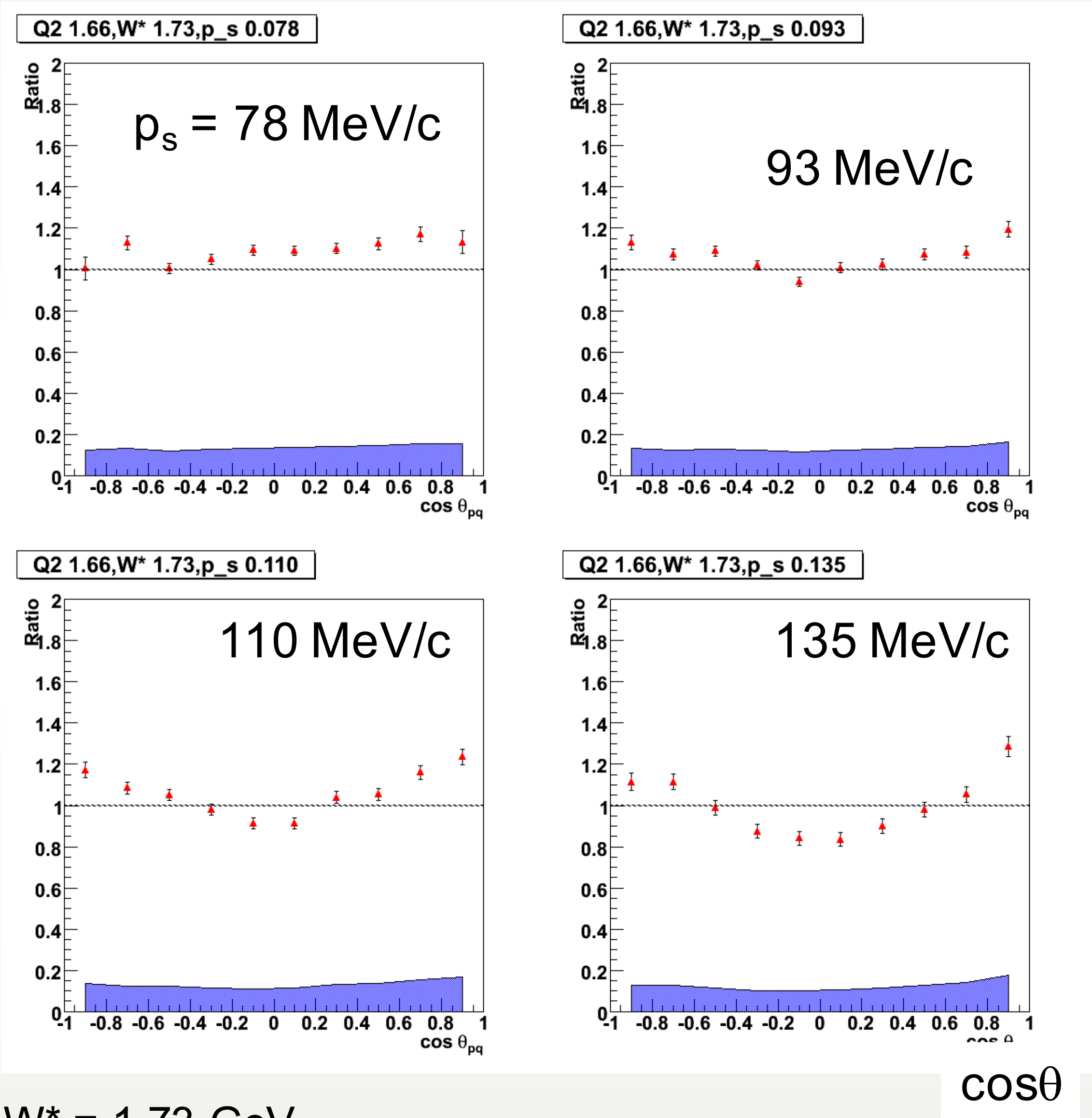
W* [GeV]

Extracted "effective structure function" F_{2n}

- Data have radiative elastic tail subtracted
- Simulation uses simple spectator model, radiative effects, full model of RTPC and CLAS

Results from BoNuS (v)

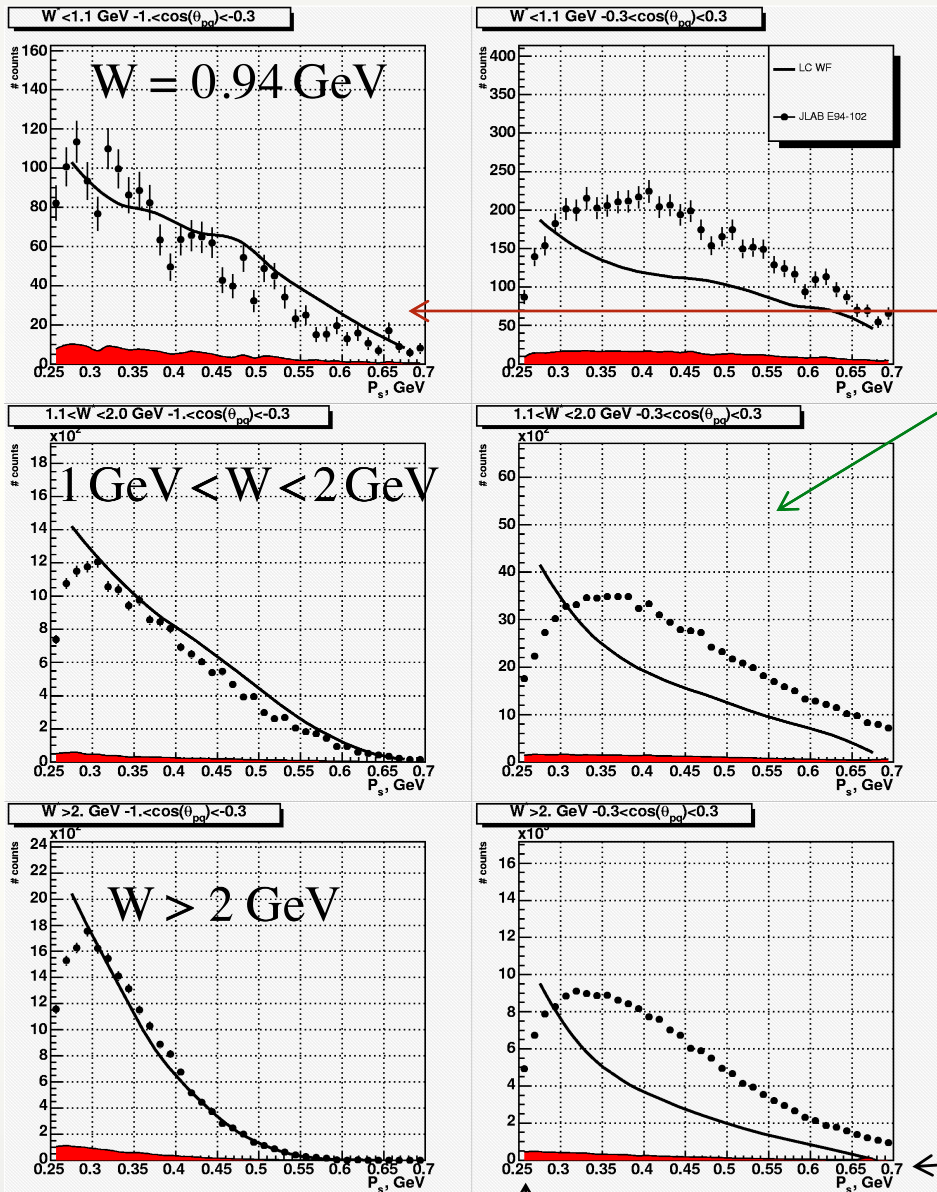
Testing the Spectator Assumption - dependence on θ_{pq}



- So far, no strong deviations from naïve PWIA spectator picture at lower spectator momenta
- Possible indication of θ-dependence at higher p_s
- Have systematics for a wide range in Q^2, W* and beam energies

W* = 1.73 GeV
Q^2 = 1.66 $(GeV/c)^2$

Results from “Deeps” : Momentum Distribution



Vertical axis: Number of events

Horizontal axis: Proton momenta from 250 to 700 MeV/c

Left: Angular range > 107.5^{O}

Right: Angular range 72.5^{O} - 107.5^{O}

3 different ranges in the final state mass W of the unobserved struck neutrons

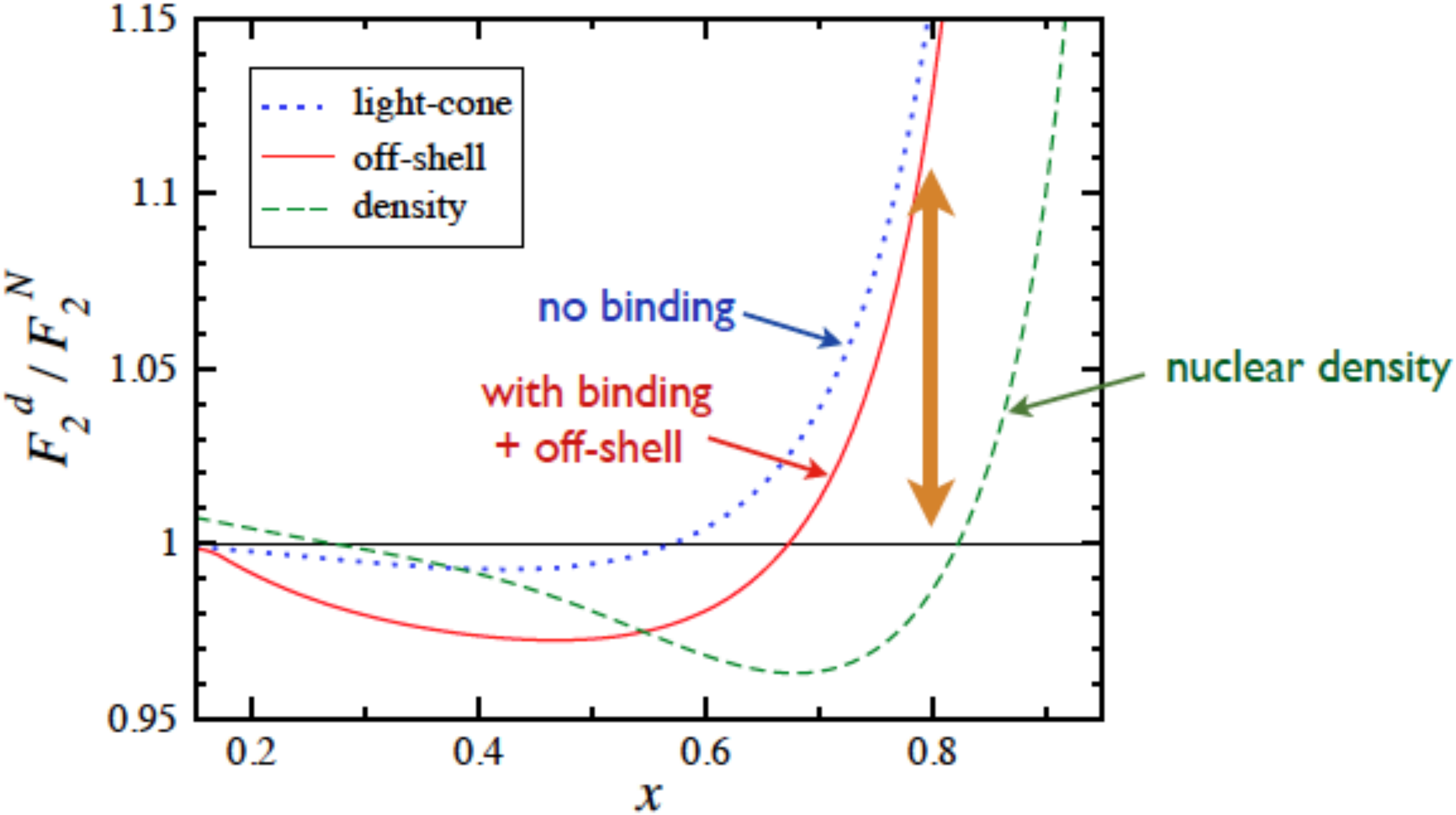
PWIA model with “light cone”-wave function for deuterium

700 MeV/c

P_s

250 MeV/c

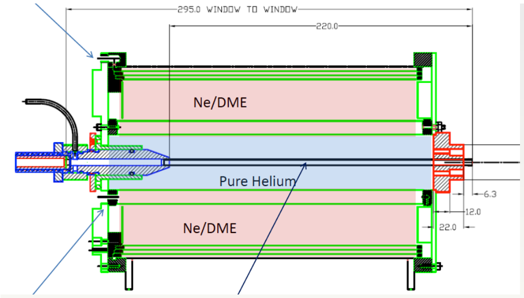
EMC effect in deuteron

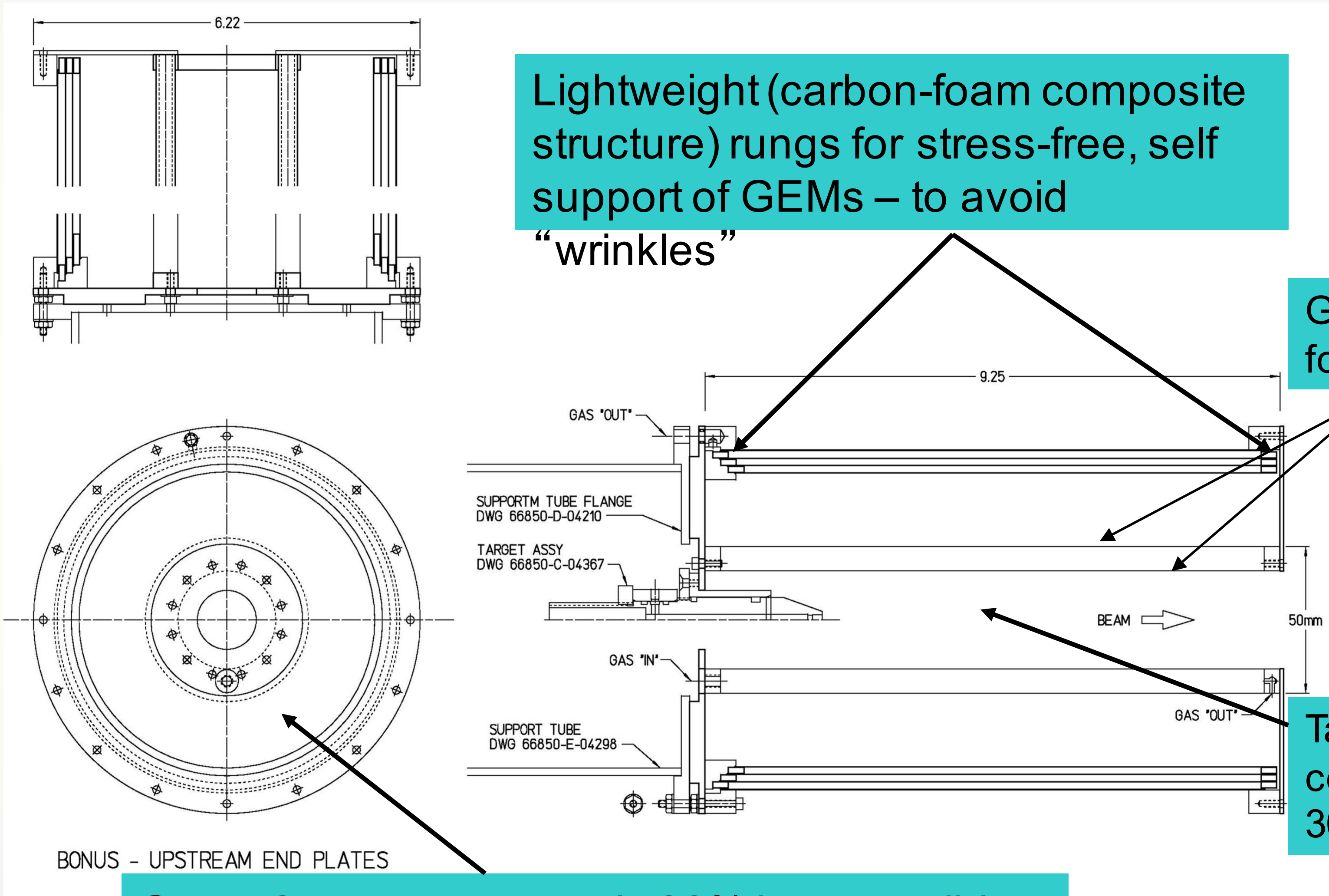


→ using off-shell model, will get *larger* neutron *cf. light-cone* model

→ but will get *smaller* neutron *cf. no nuclear effects* or *density* model

The New RTPC



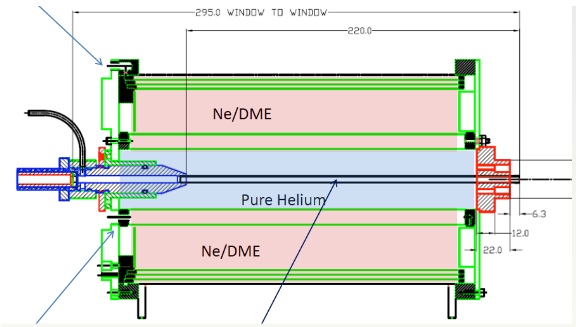


Lightweight (carbon-foam composite structure) rungs for stress-free, self support of GEMs – to avoid "wrinkles"

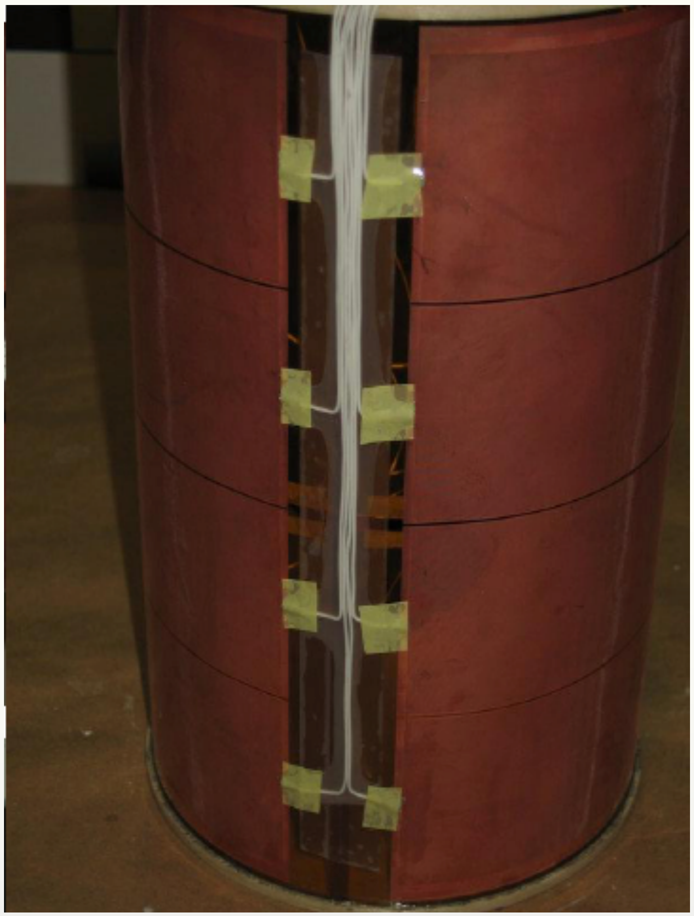
Ground and cathode foils, each 6μm thick

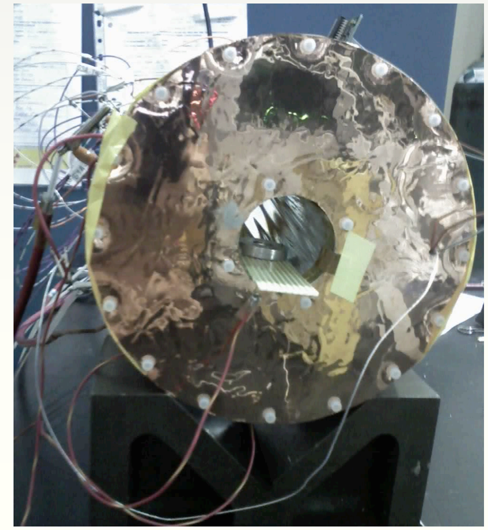
Target region - new cell – ID 4mm, 30μm thick wall

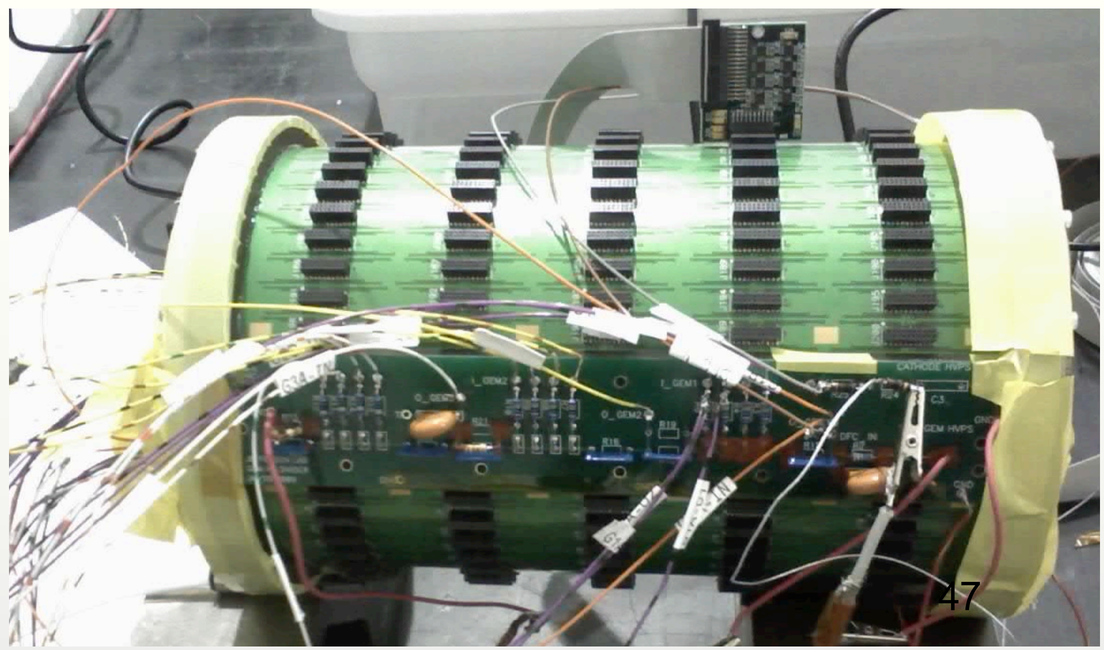
Open, 2π geometry – only 80% is accessible due to the GEM and readout pad sizes



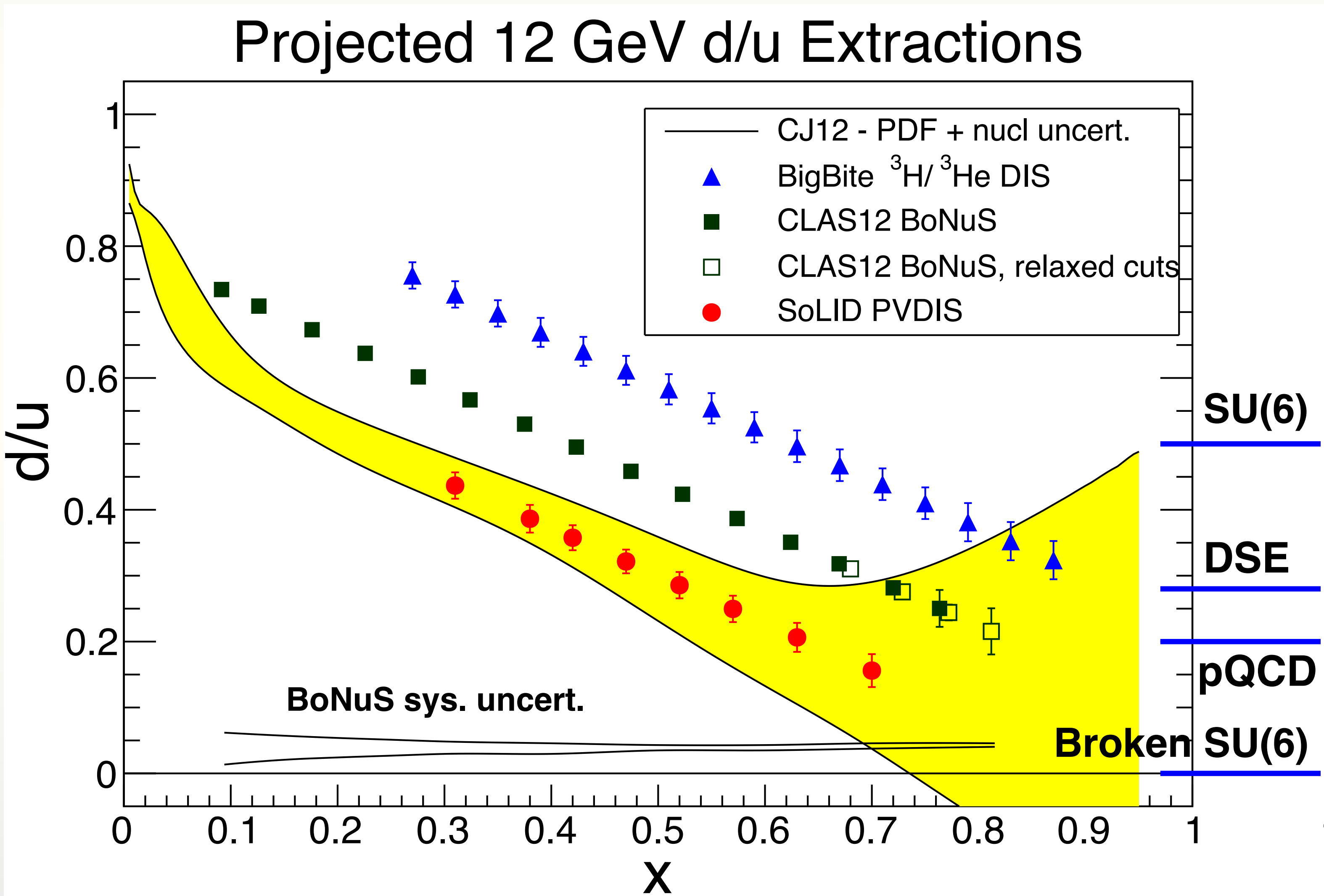
The New RTPC (ii)



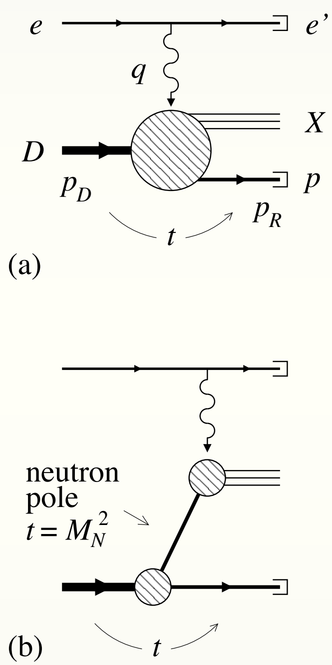


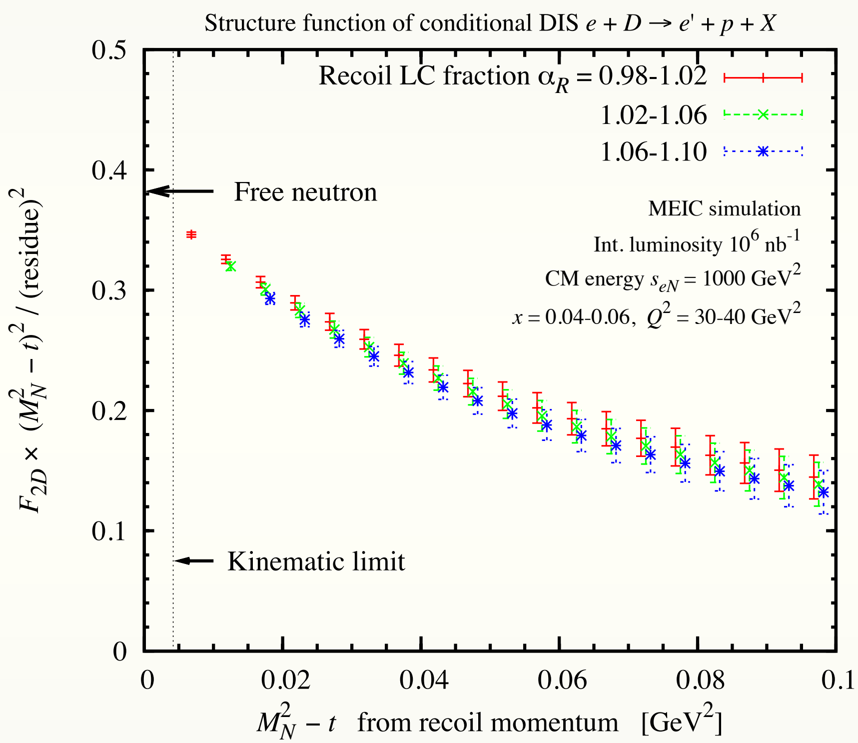


The future: JLab at 11 GeV



The more distant future: EIC





(from GEANT4)